Through the Looking Glass: Investigating Cognitive Biases in Loneliness using Virtual Reality

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Abstract

Loneliness is a complex and multifaceted phenomenon with adverse consequences for both physical and mental health. Despite growing attention, the mechanisms underlying loneliness remain insufficiently understood. Hence, this PhD thesis aimed to integrate theoretical, psychological, cognitive, behavioural, and methodological perspectives to advance the scientific understanding of loneliness. *Chapter 1* provided multidisciplinary introduction to loneliness by synthesising evolutionary, neuroscientific, cognitive-behavioural and social frameworks. *Chapter 2* systematically reviewed previous experimental studies on cognitive biases in loneliness, particularly *attention, interpretation* and *approach-avoidance biases*, which identified critical methodological, empirical, population and evidence gaps. *Chapter 3* employed multivariate modelling to examine sociodemographic, psychological, behavioural and social predictors of loneliness, highlighting alexithymia as a potential central driver, with depression and social anxiety acting as associated mechanisms; avoidance as a behavioural pathway and interpersonal trust as a critical protective factor in loneliness-related processes. *Chapter 4* investigated attention and interpretation biases in facial emotion processing across ages, *adolescent, young, middle age* and *older adults*, in loneliness providing novel contributions on age-specific differences in those biases while also providing partial support for current cognitive models of loneliness. *Chapter 5* extended the understanding of cognitive biases by examining real-time approach-avoidance behaviours towards emotional stimuli in ecologically valid immersive virtual reality environment, offering novel insights into the behavioural avoidance tendencies of lonely individuals. *Chapter 6* integrated behavioural and physiological measures within a virtual reality paradigm to explore interpersonal distance and heart rate variability, demonstrating that loneliness was associated with increased interpersonal distance during social observation, and lower heart rate variability during social engagement which ultimately offered novel understanding of loneliness. *Chapter 7* collectively refined the findings, and presented *"The Cascade Model of Loneliness"*, establishing loneliness as a dynamic biopsychosocial process with cognitive, behavioural and physiological mechanisms, paving the way for both scientific innovation and translational impact in addressing one of the most pressing public health challenges of our time.

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List of Abbreviations

Abbreviation	Full Term
AAB	Approach-Avoidance Bias
ACC	Anterior Cingulate Cortex
AI	Artificial Intelligence
AMPD	Alternative Model for Personality Disorders
AMY	Amygdala
ANS	Autonomic Nervous System
APA	American Psychological Association
AR	Augmented Reality
BDI-II	Beck Depression Inventory-II
BFNE	Brief Fear of Negative Evaluation Scale
BOLD	Blood Oxygen Level Dependent
CBAS	Cognitive Behavior Avoidance Scale
CBT	Cognitive Behavioural Therapy
CDI	Children's Depression Inventory
CES-D	Center for Epidemiologic Studies Depression Scale
CESD-R	Center for Epidemiologic Studies Depression Scale–Revised
CI	Confidence Interval
CNS	Central Nervous System
COV	Coefficient of Variation
CS	Conditioned Stimulus
dACC/AI	Dorsal Anterior Cingulate Cortex and Anterior Insula
DANVA-2	Diagnostic Analysis of Nonverbal Accuracy
DASS	Depression Anxiety Stress Scales
DASS-21	Depression, Anxiety, and Stress Scale–21
DLPFC	Dorsolateral Prefrontal Cortex
ECG	Electrocardiogram
EEG	Electroencephalogram
EMG	Electromyography
ERP	Event-Related Potential
fMRI	Functional Magnetic Resonance Imaging
GAD-7	Generalized Anxiety Disorder Scale-7
GDS	Geriatric Depression Scale
GSR	Galvanic Skin Response
GTS	General Trust Scale
HAB-Q	Hostile Attribution Bias Questionnaire
HCI	Human-Computer Interaction
HF-HRV	High-Frequency Heart Rate Variability
HR	Heart Rate
HRV	Heart Rate Variability
IAS	Interaction Anxiousness Scale
IAPS	International Affective Picture System
IBI	Interbeat Interval

Abbreviation	Full Term
ICD	International Classification of Diseases
IPD	Interpersonal Distance
IPQ	Igroup Presence Questionnaire
LACA	Loneliness and Aloneness Scale for Children and Adolescents
LAS-CA	Loneliness and Social Dissatisfaction Questionnaire for Children and Adolescents
LL	Lower Limit
LMM	Linear Mixed Model
LSDQ	Loneliness and Social Dissatisfaction Questionnaire
LPP	Late Positive Potential
MEAQ	Multidimensional Experiential Avoidance Questionnaire
N	Sample Size
NIM	Neurovisceral Integration Model
OFC	Orbitofrontal Cortex
OR	Odds Ratio
PANAS	Positive and Negative Affect Schedule
PFC	Prefrontal Cortex
PHQ-9	Patient Health Questionnaire-9
PNS	Parasympathetic Nervous System
PSY	Psychology
PTSD	Post-Traumatic Stress Disorder
R	Pearson Correlation Coefficient
REML	Restricted Maximum Likelihood
ROI	Region of Interest
RSFC	Resting-State Functional Connectivity
SAD	Social Anxiety Disorder
SAM-CA	Self-Assessment Manikin for Children and Adolescents
SASA	Social Anxiety Scale for Adolescents
SD-WISE	San Diego Wisdom Scale
SE	Standard Error
SELSA-S	Social and Emotional Loneliness Scale for Adults – Short Form
SIAS	Social Interaction Anxiety Scale
SMFQ	Short Mood and Feelings Questionnaire
SNS	Sympathetic Nervous System
SPAI-18	Social Phobia and Anxiety Inventory – 18 Item Version
SPIN	Social Phobia Inventory
SPSS	Statistical Package for the Social Sciences
SFT	Social Safety Theory
SSVEP	Steady-State Visual Evoked Potential
STAI-AD	State-Trait Anxiety Inventory – Adult Version
STS	Social Threat Scale
TMS	Transcranial Magnetic Stimulation
UCLA	University of California, Los Angeles Loneliness Scale
UEA	University of East Anglia
UL	Upper Limit
VAS	Visual Analogue Scale
VR	Virtual Reality
XR	Mixed Reality

Foreword

My interest in the psychology of human connection was sparked long before I entered academia. Through clinical practice, cross-cultural experience, and countless conversations with family, friends, teachers, students and strangers. I have observed how profoundly our inner worlds are shaped by the presence or absence of emotional atonement from others. These early encounters left me with one enduring question: ***What allows us to feel truly seen?*** *During this PhD, that question took on scientific form, combining behavioural paradigms, virtual reality simulations, and statistical modelling, I sought to better understand cognitive biases that underlie loneliness. My aim was not only to investigate loneliness as a psychological state, but to explore it as a deeply human signal, an embodied expression of our need to belong.*

Hence, this thesis is the culmination of a journey that has been as personal as it has been academic. When I first set out to explore the cognitive and emotional dimensions of loneliness, I had no idea how much the subject would come to resonate with my own experiences and those around me in this fine city, called Norwich. What began as an academic investigation into cognitive biases in loneliness evolved into a mirror reflecting the nuances of my own path. Throughout this journey, I found myself drawn, perhaps inevitably, to the stories of others and I was captivated by the uniqueness of human lives. I listened to the stories, not as a researcher or a psychologist but purely as another human being, of older people resting on park benches at Chapelfield Gardens, to Gen Z students opening up over oat lattes at Ziggy's Coffee on campus, and to local young people speaking freely over pints in the pubs of Norwich. Different voices, different backgrounds, yet a shared thread: a deep, often quiet yearning for meaningful connection. These candid moments reminded me that loneliness does not discriminate. Beneath the surface of everyday conversation, people carry a hope to be seen, heard, understood, and emotionally met.

Ultimately, this thesis is about the paradox of human connection: our simultaneous desire to be close and our fear of being vulnerable. It is about how we protect ourselves, sometimes at the cost of the very intimacy we crave. It is about our shared humanity, our yearning to be seen, and the psychological patterns that both help and hinder our ability to connect. I hope that this PhD thesis speaks not only to the scientific community but also those who have experienced loneliness in many forms and who seek to understand it not as a flaw, but as a fundamental signal of our need for connection with others and meaningful relationships.

To all those who have felt unseen, unheard and not understood, this is for you.

Ceyda

Acknowledgments

This PhD has been the most challenging, demanding and transformative journey of my life. It has tested the limits of my intellect, my resilience, and sometimes even my hope. There were moments of clarity and discovery, but also long stretches of uncertainty, isolation, and exhaustion, times when the finish line felt impossibly distant. This PhD journey was filled with bizarre explorations and constant questioning of how we see the world as we are. Using virtual reality goggles as my looking glass in *"Alice's Adventures in Wonderland",* I spent days, months, and years reading about cognitive biases and how they shape our perceptions of others and the world that surround us in this *Lonelyland Norwich*. Much like Alice's adventures, nothing was quite as it seemed. The deeper I went, the more questions I found. And yet, through it all, I was never truly *alone*. I have been incredibly fortunate to be surrounded by people who lifted me up when I fell, believed in me when I doubted myself, and gave me strength when I had none left to give. I am deeply grateful to my supervisors, whose guidance shaped not only this thesis but my growth as a researcher and a person. They gave me the greatest gift a mentor can offer: the freedom to do science with curiosity, courage and critical thinking. Their patience, encouragement, and unwavering belief in my potential helped me keep going, even when I lost sight of my own path. Hence, this PhD journey was walked with the steady footsteps of those who stayed beside me. It was written in the quiet of long nights, in the chaos of deadlines, and in moments of existential crises. It carries with it the imprint of every conversation that challenged me, every hand that reached out when I needed it most, and every small act of kindness that gave me the courage to continue. This is not just a document of research, it is a testament to endurance, community, and the fragile, fierce hope that we carry when we dare to ask difficult questions and try to find meaning in the answers. For all these reasons and more, there are many people I am profoundly grateful to.

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Publications and Presentations

Publications from PhD research

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Kiyak, C., Edwards, G., & Bengtsson, S. (in preparation). Lonely Minds: Attention and Interpretation Bias in Facial Emotion Processing across Ages in Loneliness

Kiyak, C., Edwards, G., & Bengtsson, S. (in preparation). Mapping Loneliness: A Multivariate Exploration of Psychological, Cognitive and Behavioural Predictors

Kiyak, C., Edwards, G., & Bengtsson, S. (under review). Loneliness Paradox: A Scoping Review of Experimental Studies on Cognitive Biases in Loneliness

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Book chapters

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Disclaimer III: In this thesis, the terms "sex" and "gender" are used distinctly, with "sex" referring to biological differences and "gender" focusing on social and cultural influences. The author recognizes that both sex and gender exist on spectrums and that binary classifications may not fully capture the diversity of human experiences. While efforts have been made to ensure inclusivity, some analyses are limited by the binary categories provided in the datasets or literature reviewed. The integration of sex and gender throughout this thesis reflects a commitment to scientifically rigorous, socially responsible, and inclusive research practices.

Disclaimer IV: Ethnicity data were collected using a demographic questionnaire and classified in accordance with UK government standards, following official guidance on ethnic group categorisation used in national statistics.

Disclaimer V: A deliberate effort has been made by the author to incorporate a variety of figures throughout this thesis to enhance the accessibility and comprehension for readers with diverse learning skills and neurodiversity. The integration of visual elements aims to complement the text, providing alternative pathways for engagement and interpretation of the thesis. This approach aims to acknowledge and value the neurodiversity in cognitive and perceptual processing styles, ensuring the thesis is more inclusive and adaptable to a broader audience. All images included are either original creations by the author or sourced from materials that are legally permitted for academic use and distribution.

Disclaimer VI: RStudio coding scripts were initially drafted with the support of AI-assisted tools to aid in analysis and proofreading software was used for minor language refinement (grammar, spelling, and punctuation). All outputs were carefully reviewed, revised, verified, and adapted by the author before use. The author accepts full responsibility for the accuracy, validity, and interpretation of all analyses and results presented. The use of these tools was consistent with institutional guidance, and all ideas, analyses, and interpretations are the author's own.

Thesis Overview

What contributes to a good life? Over the past 80 years, the Harvard Study of Adult Development has been seeking to answer this big question in their longitudinal study on happiness (Waldinger & Schulz, 2023). They discovered that strongest predictor contributing to overall life satisfaction was not wealth, fame, or even general health but rather the maintenance of close interpersonal relationships.

Particularly, the COVID-19 pandemic with the implementation of social isolation measures worldwide has increased the academic and public attention on loneliness (Killgore et al., 2020; Bu et al., 2020). In recognition of its significance as a public health concern, the United Kingdom (UK) appointed the world's first "Ministry of Loneliness" in 2018 (Bruce et al., 2019), inspiring similar initiative globally, with Japan following in 2021 by appointing their own "Minister for Loneliness" to address rising suicide rates exacerbated by social isolation and loneliness (Kawanishi, 2022). Moreover, the United States of America (USA) appointed its first "Ambassador to Loneliness" in 2022 to combat the growing social isolation where the US Surgeon General declared "*a loneliness epidemic*" (Office of the Governor of New York, 2022).

Loneliness is a complex phenomenon impacting individuals' both physical and mental health along with the social life. Yet it remains one of the least understood and conceptualised phenomenon despite of empirical research over the last few decades. Although it has gained recognition as a global public health issue, our understanding on its underlying mechanisms is still limited, and largely depending on overly generalised theoretical models that risk oversimplifying its complex biopsychosocial

roots. Hence, in this PhD thesis, I aimed to critically address this gap by investigating loneliness not merely as a feeling or social condition, but also as a cognitive, perceptual and behavioural concept shaped by cognitive biases affecting the processing of social and emotional information during interpersonal interactions. To achieve this aim:

Chapter 1, *Multidisciplinary Introduction to Loneliness*, I aimed to provide a comprehensive, multidisciplinary framework for understanding loneliness by integrating theoretical, empirical, and neurobiological perspectives. The chapter began by defining and distinguishing loneliness from similar concepts such as social isolation, solitude, and aloneness. It subsequently introduced a taxonomy of loneliness, covering emotional, social, collective, and existential dimensions, along with a distinction between situational and chronic loneliness. Integrative theoretical frameworks were explored, including evolutionary, neuroscientific and cognitive-behavioural models, as well as social theories. I also examined biological, psychological, sociocultural and technological risk factors. The chapter also highlighted the rising global prevalence of loneliness across all age groups, with notable cultural and regional variations. The chapter concluded with a discussion of the consequences of loneliness, highlighting its impact on physical health, mental health, and broader societal outcomes. Together, these sections established a comprehensive foundation that informs and contextualises the empirical investigations presented in subsequent chapters.

Chapter 2, *Study 1: Scoping Review*, I aimed to systematically map and synthesise experimental research investigating how cognitive biases, specifically attention, interpretation, and approach-avoidance biases, contribute to the experience and maintenance of loneliness. Grounded in the Social Information Processing framework

and evolutionary models, this scoping review analysed 28 experimental studies using behavioural, cognitive, neuroimaging, and physiological methods across different age groups. This review not only clarified key mechanisms of loneliness but also identified methodological gaps and proposed directions for the regression studies and experiments in the subsequent chapters.

Chapter 3, *Study 2: Multivariate Modelling of Loneliness*, I explored key sociodemographic, psychological, behavioural and social predictors of loneliness using multivariate modelling in a three different large adult sample. After applying hierarchical regression and exploratory interaction modelling, the findings offered a nuanced, multidimensional understanding of loneliness and informed the hypotheses and sample selection of the experimental studies in the subsequent chapters.

Chapter 4, *Study 3: Attention and Interpretation Bias in Facial Emotion Processing***,** I addressed the empirical gaps in research identified in Scoping Review in Chapter 2 and designed an advanced online experimental tasks to explore attention and interpretation biases, focusing on how individuals with high vs low loneliness process emotional facial emotions across ages. First, I conducted a pilot study for in-depth investigation into the temporal dynamics of emotion perception and the interpretation of ambiguous facial expressions to provide a more robust investigation for the main experiments. With the insights gained from the pilot study, two experiments were conducted with age-specific facial emotion processing tasks; video clips of faces with neutral expressions that gradually morphed into full emotional expressions to measure attentional sensitivity and decoding accuracy; and static images with neutral faces and different emotional

intensity to measure misinterpretation of neutral faces and decoding accuracy of ambiguous faces.

Chapter 5, *Study 4: Approach-Avoidance Bias Towards Emotional Cues in Loneliness***,** I investigated how loneliness influences embodied approach–avoidance responses to emotional cues in virtual reality (VR). Using a novel immersive VR paradigm, I conducted two experiments at Radboud University in Netherlands and University of East Anglia in UK. Participants interacted with virtual avatars displaying neutral, happy, angry, or sad facial expressions, while their head movements were tracked. These two experiments offered ecologically valid insights into the embodied postural responses associated with loneliness and demonstrated the value of VR in capturing subtle social avoidance behaviours towards facial emotions.

Chapter 6, *Study 5: Loneliness and Avoidance: Physiological and Behavioural Responses***,** I explored the relationship between loneliness and physiological responses and behavioural avoidance in VR, specifically investigating heart rate variability (HRV) and interpersonal distance (IPD) across different social and non-social contexts. This study bridged a critical gap in loneliness literature and provided a significant understanding of how loneliness influences social preferences and interactions by examining behavioural, physiological and social factors.

Chapter 7, General *Discussion and Conclusion,* I integrated findings across five studies to present a cohesive narrative on the mechanisms and expressions of loneliness. Drawing from multidisciplinary theory and experimental data, including immersive virtual reality, I synthesised results to reveal a sequential pattern and proposed *the*

Cascade Model of Loneliness, illustrating how predisposing vulnerabilities trigger the subjective experience of loneliness, which in turn activates cognitive biases, leads to behavioural avoidance, and if trust is impaired, ultimately reinforces a cycle of chronic loneliness through neurocognitive and physiological dysregulation. Furthermore, this chapter discussed the theoretical and practical implications of the findings and measurements, critically evaluated methodological limitations, and proposed future directions to refine our understanding of loneliness through more precise and ecologically valid tools, while offering psychological interventions to target loneliness loop.

Therefore, this PhD thesis, rooted in an integrative multidisciplinary framework, aims to explore how *cognitive biases* contribute to the experience of loneliness. Importantly, I challenged the assumption that loneliness is simply the result of lacking social connections. My purpose of this PhD research was to unpack the cognitive and behavioural underpinnings of loneliness which could contribute identifying potential cognitive targets for more effective and personalised psychological interventions. I hope that the findings from this PhD thesis will have significant implications for research, theory, and clinical practice, particularly in the development of VR-based psychological interventions and Artificial Intelligence (AI) solutions, and to public health policy by reframing loneliness through the lens of cognitive and clinical psychology combined with technological innovation.

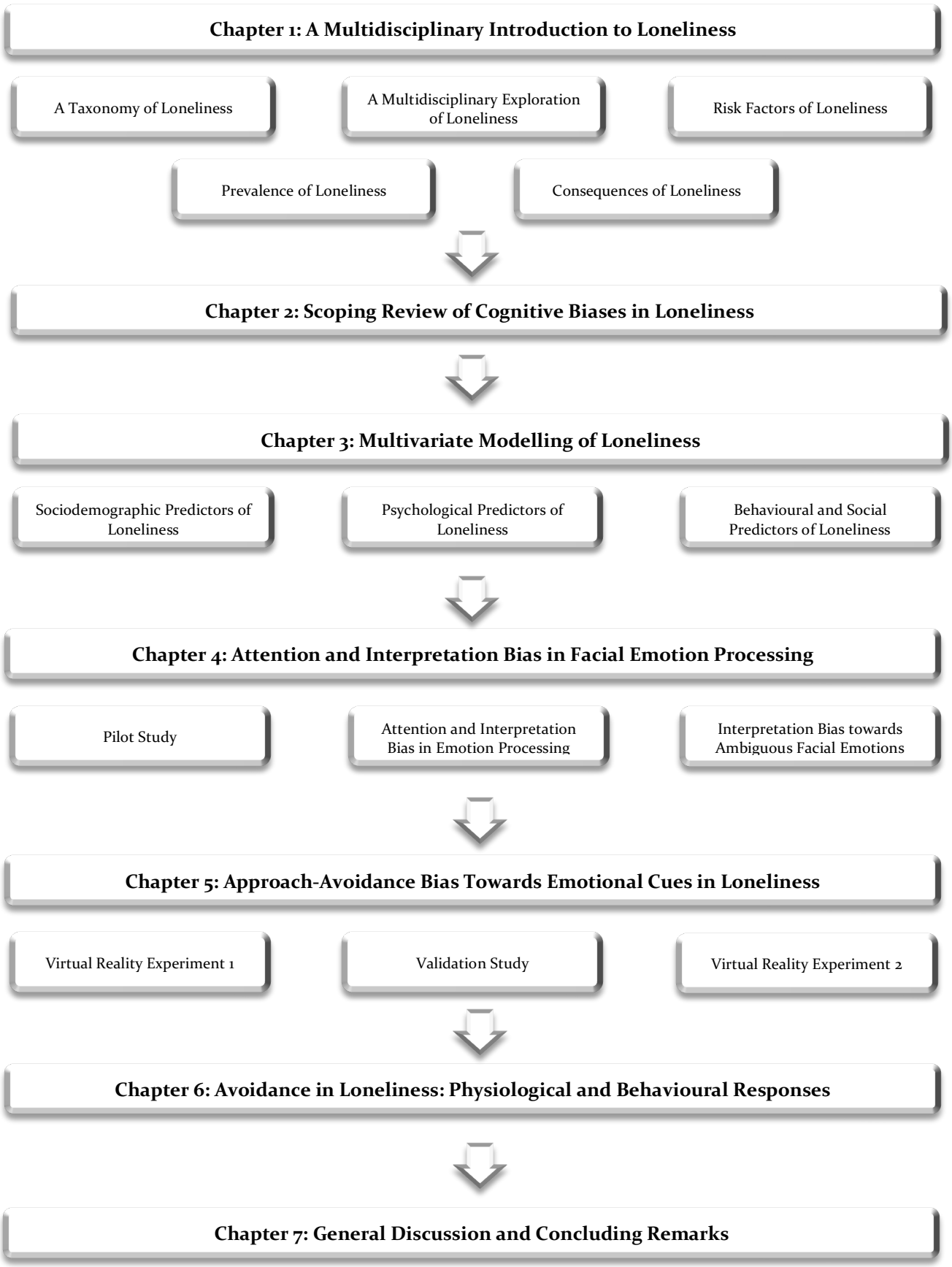


Figure 1. Overview of Thesis Structure and Chapter Progression

CHAPTER 1

A Multidisciplinary Introduction to Loneliness

"If you want to walk fast, walk alone; if you want to walk far, walk together."
African Proverb

1. A Taxonomy of Loneliness: Concepts, Types and Dimensions

Loneliness is a universal human experience and an inevitable component of existence that most human beings encounter at some point in their lives. Theoretically, loneliness is described as *"the subjective discrepancy between one's desired and one's (perceived) existing interpersonal relations"* (Peplau & Perlman, 1982, *p.31*). The feeling of loneliness motivates us to strengthen our social connections and protect ourselves from the dangers of living on the social perimeter (Cacioppo et al., 2015; Bangee & Qualter, 2018). Therefore, episodes of loneliness are considered normal and essential for survival, however the consequences of chronic loneliness can be detrimental. According to recent studies, loneliness had a widespread impact on both physical and psychological health and leads to premature mortality and morbidity (Holt-Lunstad, 2021). Moreover, loneliness increases the risk of a range of psychological issues such as depression, anxiety, and dementia (Landeiro et al., 2017). Loneliness affects people of all ages, defying the widespread stereotype that it only affects older people (Hawkley et al., 2022). Despite being stigmatised, trivialised, and overlooked, loneliness is emerging as a significant global public health concern (Cacioppo & Cacioppo, 2018a). Yet, it remains a complicated and poorly understood phenomenon for individuals, researchers, clinicians, and policymakers (Mansfield et al., 2021).

The subjective and context-dependent components of loneliness defy singular straightforward explanations (Banerjee & Rai, 2020). Therefore, loneliness requires a comprehensive understanding and exploration of its conceptual underpinnings due to its multidisciplinary dimensions and multifaceted characteristics. Additionally, there is

a growing recognition of its social and societal dimensions, such as cultural norms, social structures and the role of technology on loneliness (Smith et al., 2021). Therefore, the following section explores the conceptualisation of loneliness, examining its definitions and distinctions from related constructs.

1.1. Conceptualisation of Loneliness

Loneliness is one of the least conceptualised psychological phenomena (Motta, 2021). Over the last decades, empirical studies offered a range of definitions of loneliness to distinguish between loneliness, social isolation, solitude, and aloneness, which were often used interchangeably (Borg & Willoughby, 2023; Goossens, 2018).

A review of loneliness literature (Heinrich & Gullone, 2006) provided examples of various definitions focusing on clinical perspective, empirical psychological research, social relationships and the human need to belong. Drawing on this, Motta (2021) provided five dominant definitions of loneliness, which help literature conceptualise loneliness. The first type of definition is based on ***'social needs'*** inspired by Bowlby's (1979) "Attachment Theory", which is *"not necessarily intimate or confident in nature but rather enables the meeting of one's inherent social needs such as attachment, social integration, nurturance, reassurance of worth, reliance alliance, and guidance"* (Heinrich & Gullone, 2006, *p. 708*). The second type of definition is based on ***'cognitive discrepancy'*** in which the individual experiences an aversive state when there is a discrepancy between the interpersonal relationships they wish to have and what they perceive they have (Peplau & Perlman, 1982). This definition is particularly crucial for the overall thesis as cognitive discrepancy draws on "Attribution Theory" which refers a cognitive processing in social situations where people interpret, explain, and predict

others' and their behaviours through internal (dispositional) and external (situational) attributions (Fiske & Taylor, 1979). In the context of loneliness, lonely individuals are considered to attribute causality in terms of interpersonal relationships with a maladaptive schema (e.g., cognitive biases) meaning a self-perpetuating loop where attribution biases *contribute* loneliness, and loneliness *amplifies* attribution biases (Motta, 2021). The third type of definition is based on '***the interactionist approach***', which suggests that social relations are shaped by characteristic traits (e.g., social anxiety, introversion), situational (e.g., migration, separation) and cultural factors (e.g., expectations from a social and romantic relationship). The fourth type of definition is based on ***'deficits in social relationships'*** in which loneliness is seen as a multifaceted response causing *"negative feelings such as desperation, depression, impatient boredom, and self-deprecation* (Motta, 2021); *and negative attitudes about oneself, other people, and about the causes of events; as well as passive, self-absorbed, and ineffective social behaviour"* (Heinrich & Gullone, 2006, *p. 712*). Finally, the fifth definition is based on ***'belongingness',*** which is an inevitable part of human existence regardless of age, economic background, social, health or marital status (Frie, 2017; Mijuskovic, 2012).

These definitions of loneliness highlight its social, psychological and existential dimensions while providing a foundation for a deeper exploration of how it distinguishes from related constructs such as social isolation, aloneness, and solitude. While ***loneliness*** refers to a subjective emotional state determined by their quality (Green et al., 2001); ***social isolation*** is an objective measure of the quantity and the quality of an individual's social interactions (Reinhardt et al., 2021), such as being separated and/or excluded (e.g., COVID-19 pandemic quarantines). While social isolation can increase the risk of loneliness, more social connections do not necessarily

reduce the feeling of loneliness, as loneliness is about the quality of the formed relationships rather than the quantity of them. Moreover, while ***solitude*** is also a subjective feeling like loneliness, it is described as a state of the voluntary external condition often associated with a positive state of being alone (e.g., self-discovery and relaxation; Thomas, 2023; Morgan & Burholt, 2020). For instance, some people might find fulfilment and meaning in solitude, using the space to thrive in what they feel is important. Conversely, other people may have a rich social life and strong family ties, but they still experience a deep sense of loneliness. Meanwhile, ***aloneness*** refers to an objective physical state of having no one around and/or being alone for protracted periods of time without negative or positive connotations (e.g., living alone, studying at a library alone; Nguyen et al., 2021).

1.2. Types and Dimensions of Loneliness

The classification of loneliness based on types and dimensions has been extensively studied in the literature among the various frameworks for understanding it (Motta, 2021; Agashe et al., 2021). However, one key typology concerning the duration of loneliness received only limited attention in the literature (de Jong Gierveld & Raadschelders, 1982). This framework identifies two primary types of loneliness: situational (transient) loneliness and chronic (prolonged) loneliness.

i. **Situational (transient) loneliness:** *Situational loneliness* refers to a temporary state of feeling isolated or/and disconnected (Blai, 1989). It typically rests upon stressful life events or changes, such as losing a loved one or a job, moving to a new place, separation, or retirement (Shiovitz-Ezra & Ayalon, 2010). Previous studies mostly used single item questions to measure state or context-sensitive

feelings of loneliness (Mund et al., 2020; Saporta et al., 2021). Situational loneliness usually lessens over time as individuals adjust the new transition and/or rebuild their social networks (Serbin, 1983).

ii. **Chronic (prolonged) loneliness:** *Chronic loneliness* is characterised by a prolonged state arising from a person's long-standing difficulty in forming or maintaining meaningful social connections (Shiovitz-Ezra & Ayalon, 2010). It is often measured with widely used UCLA Loneliness Scale to assess stable and long-term feelings of loneliness (Russell, 1996). Unlike situational loneliness, chronic loneliness can lead to social withdrawal, making it more challenging for people to seek the support they need.

Situational loneliness might seem to only differ from chronic loneliness in terms of the duration of time, however, there are several variables that are separating them from each other. For instance, while situational loneliness arises from current specific events or life transitions with milder psychological effects, which could improve as people seek new social opportunities (Lim et al., 2020; Spithoven et al., 2019), chronic loneliness is often rooted in deeper emotional or social barriers with more severe psychological consequences, such as persistent depression, anxiety, and reduced life satisfaction (Mund et al., 2020; Goossens et al., 2022). Understanding the distinction between situational and chronic loneliness is essential to examine the multidimensional nature of it, which further reveals its complexity and the diverse ways it can appear in people's lives.

Different domains of loneliness have been also reflected in literature so far. One of the leading loneliness researchers, Cacioppo et al. (2016), proposed three dimensions of loneliness: *intimate, relational*, and *collective*, each corresponding to a person's

attentional space: *personal, relational* and *collective*. These dimensions align with prominent loneliness researchers Weiss's (1975) framework of loneliness and Dunbar's (2014) models of social networks where they examined the social spaces regarding three dimensions of loneliness. These two models have been elaborated in the following sections where the distinct dimensions of loneliness are critically examined.

i. **Emotional (personal/intimate) loneliness:** Emotional loneliness stems from the absence of a "significant someone" with an intimate attachment relationship (Motta, 2021; Cacioppo et al., 2015; Cramer & Berry, 1999). According to Dunbar, this dimension is the "*support clique/inner core*", which can include up to 5 people and comprises the people we rely on for emotional support during crises (Dunbar, 2014). Therefore, it corresponds to "*intimate/personal*" (Hall, 1996) and "*personal*" attentional space (Ortigue et al., 2006).

ii. **Social (relational) loneliness:** Social loneliness originates from the lack of perceived connections with a broader group of contacts or an engaging social network (Van Tilburg, 2021). This dimension is referred to as a "*sympathy group*" in Dunbar's model, which can include between 15 and 50 people and comprises core social partners whom people see regularly (Dunbar, 2014). This dimension corresponds to "*social*" (Hall, 1996) or "*near extra personal*" attentional space (Ortigue et al., 2006).

iii. **Collective loneliness:** Collective loneliness originates from the perceived absence of connections within larger groups in society (e.g. national identity), and that can be at a distance in the collective space (Grace et al., 2022; Altweck et al., 2024). While collective loneliness was not defined in Weiss's model (1975), Dunbar (2014) described it as an "*active network*", which is the outermost social

layer and includes between 150 and 1500 people. This dimension corresponds to "*public*" (Hall, 1996) or "*far extra personal*" attentional space (Ortigue et al., 2006).

iv. **Existential loneliness:** Traditionally, existential loneliness was defined as an *"intrinsic and organic reality of human life"* (Moustakas, 1961, *p. 46*). It stems from the profound awareness that a human being is inherently lonely with the accompanying intolerable emptiness, sadness, longing, and alienation (Van Tilburg, 2021; Bolmsjö et al., 2019; Ettema et al., 2010). There is a growing acknowledgement of existential loneliness in the current literature (McKenna-Plumley et al., 2024; Maes et al., 2022; Victor et al., 2021; Van Tilburg, 2021). However, the role of attentional and social space in relation to existential loneliness remains largely unexplored in existing research. In this thesis, "existential loneliness" is included as a fourth dimension as it has been widely recognised in the literature for its significance in understanding the deeper, existential aspects of loneliness (Larsson, 2023; McKenna-Plumley et al., 2024; Van Tilburg, 2021; Booth, 1997; Yalom, 1980). This extension of the model encompasses the profound sense of loneliness rooted in one's search for meaning, purpose and connection to existence beyond the interpersonal and social realms. However, despite its significance, the literature does not specifically compartmentalise it into distinct spatial dimensions like social or attentional where loneliness is examined based on relational proximity, which refers how emotionally, socially, or cognitively “close” someone feels to us (Valenzuela-Garcia et al., 2021).

In conclusion, loneliness comprises *emotional, social, collective*, and *existential dimensions*, all of which contribute to a significant comprehension of the construct. Understanding its complexity requires a comprehensive multidisciplinary approach that integrates evolutionary, neuroscientific, cognitive, psychological, and social frameworks. Examining loneliness through these theoretical lenses provides complementary and critical insights into its adaptive origins and impacts.

In Table 1, the dimensions of loneliness and different compartments of space were outlined.

Table 1. The Four Dimensions of Loneliness and Different Compartments of Space*

	Social spaces			**Attentional spaces**	
	Weiss 1973	Dunbar 2014	Cacioppo et al. 2015	Hall 1966	Ortigue et al. 2006
Emotional	Emotional	Support clique/Inner core	Intimate	Intimate/ Personal	Personal
Social	Social	Sympathy group	Relational	Social	Near extra personal
Collective	-	Active network	Collective	Public	Far extra personal
Existential	-	-	-	-	-

** Table 1 was adapted from Cacioppo et al., 2016. Existential loneliness remains conceptually unanchored within existing social and attentional frameworks; hence, it is not represented in the corresponding compartments in the table.*

In Figure 2, loneliness was mapped with various definitions based on a hierarchical model of feelings of connection.

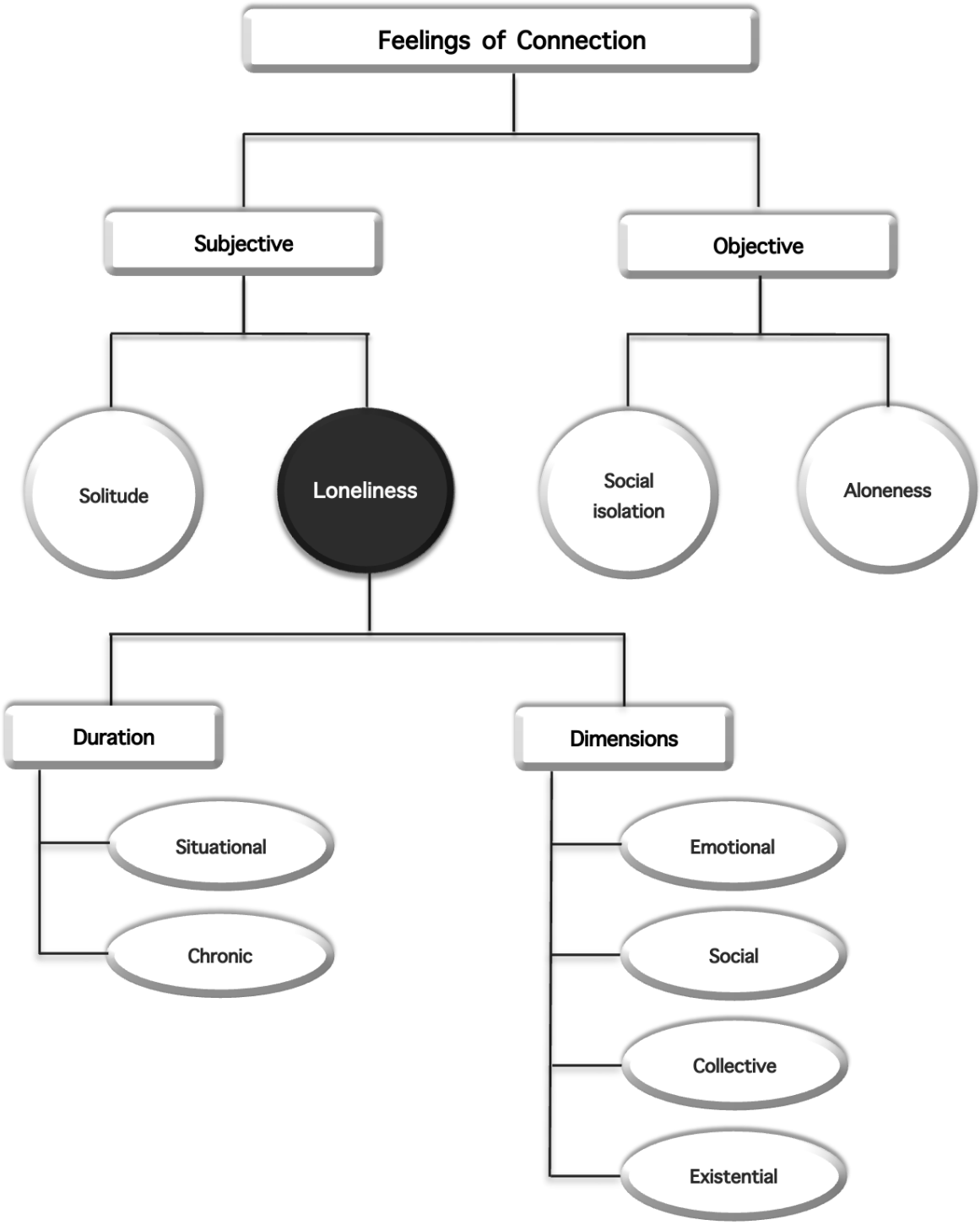


Figure 2. A Hierarchical Model of Feelings of Connection and Mapping Loneliness

Note: The dimensional structure of loneliness operates orthogonally to its temporal duration, such that each dimension, emotional, social, collective, or existential, can topographically co-occur with either situational or chronic loneliness.

2. Integrative Theoretical Frameworks of Loneliness: A Multidisciplinary Exploration

2.1. The Evolution of Loneliness

Loneliness, much like hunger, thirst and pain, serves as a fundamental signal to human beings for frayed or broken connections, as well as motivation to repair and maintain those connections (Cacioppo & Hawkley, 2010; Baumeister & Leary, 2017). Throughout human history, living in social tribes has played a vital role to secure resources and raise offspring in the survival and flourishing of the human species (Dunbar, 2014; Tomasello, 2014). Hence, understanding loneliness through this evolutionary perspective sheds light on its dual role as both a survival mechanism and a potential maladaptive response in the modern world.

2.1.1. The Evolutionary Role of Loneliness as a Survival and Adaptive Mechanism

Human beings are social species relying on a safe and secure social environment to survive and thrive (Cacioppo et al., 2014). Our ancestors formed social connections and evolved to live in couples, families, and tribes as an essential survival strategy and reproduction (Hawkley & Cacioppo, 2010; Dunbar, 1998). In ancestral societies, isolation was perceived as a significant danger as it increased the vulnerability to predators and other threats, which triggered stress and hypervigilance (Cacioppo et al., 2014). Therefore, social relationships were essential as a survival mechanism for vital resources and protection, when in danger (Cacioppo et al., 2006; Wolins, 2017). Hence, loneliness evolved as an adaptive mechanism to act as an alarm system, to address disconnection and promote behaviour change and to increase the likelihood of survival of our

ancestors (Cacioppo et al., 2014; Inagaki et al., 2016; Tomova et al., 2021). In modern life, human beings still carry this ancestral brain. This inherited brain circuitry, shaped by genetics, continues to drive hypervigilance and stress in response to perceived social isolation (Cacioppo et al., 2014).

2.1.2. Maladaptive Aspects of Loneliness in Modern Context

Cacioppo et al. (2014) proposed an "Evolutionary Model of Loneliness" to explain how loneliness may operate in the context of modern life. According to this model, loneliness increases the explicit attention to social cues, motivating people to connect with others while simultaneously increasing hypervigilance about social threats. This heightened vigilance helps protect against potential social dangers but can also lead to negative cognitive biases such as confirmatory (e.g., seeking out evidence that confirms their believes that others dislike them), attentional (e.g., selective allocation of attention to negative social cues) and memory biases (e.g., selectively focusing on past instances of social exclusion; Duck et al., 1994). These biases then reinforce loneliness through the behavioural confirmation process by validating their negative expectations of others, leading them to act negatively in a way that pushes others away (Rotenberg et al., 2004). Hence, lonely people may view themselves as passive victims in their social world even though they are active contributors through self-protective and bias-driven interactions with others (Cacioppo & Hawkley, 2005; London et al., 2007).

In modern society, this inherited mechanism, once essential for survival, can become maladaptive as these counterproductive effects of loneliness on social cognition and self-preservation may produce paradoxically self-defeating behaviours for lonely people (Cacioppo et al., 2014). Morese and Palermo (2022) expanded on Cacioppo et al.'s model (2014) by emphasising the roles of social exclusion and inclusion, highlighting

repulsion and attraction as central dynamics in social interactions. They also suggested that, over time, the cycle of repeated effects of social cognition, driven by the loneliness paradox, contributes to progressive social deprivation, physical frailty, and neurodegeneration, particularly with age intensifying the adverse consequences of chronic loneliness and stress. Overall, both models demonstrate the dynamic interplay between loneliness, social environments, and their long-term cognitive, social and biological consequences in contemporary society (Figure 3).

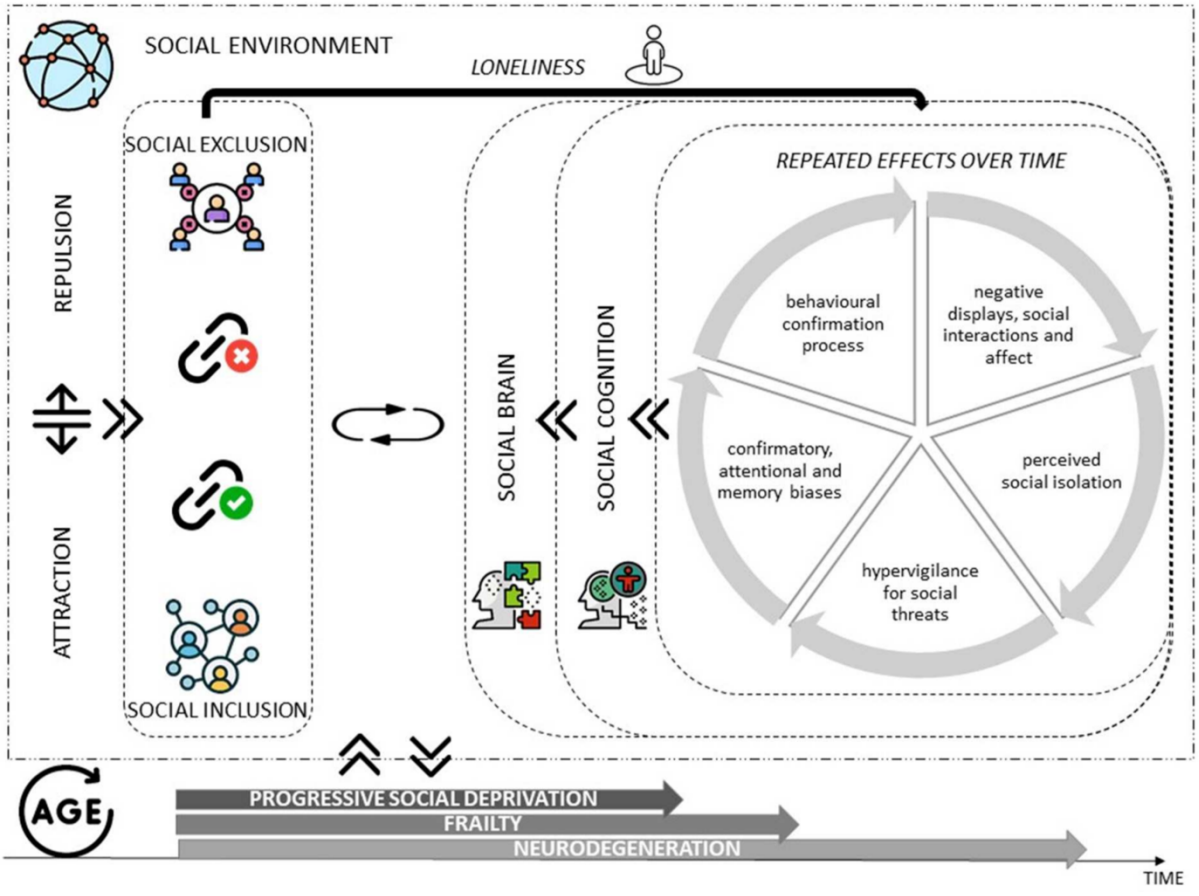


Figure 3. Morese and Palermo's Theoretical Model of Loneliness (2022)
Note: The model was adapted from Cacioppo et al. (2006) Evolutionary Model of Perceived Social Isolation. It summarises the relationships between the interactions between the individual and the social environment, and the dynamics of mutual interchange that affect the social cognition and social brain in time.

2.2. The Neuroscience of Loneliness

The human brain is a key body part for social connections (Djurdjevic et al., 2022). Neurobiological studies demonstrated that loneliness significantly impacts the structural and functional dynamics of the brain, particularly in regions critical to emotion regulation, social processing, and reward sensitivity. A recent systematic review reported that despite some mixed evidence, loneliness was consistently associated with differences in prefrontal cortex (PFC), insula, hippocampus, amygdala, and posterior superior temporal cortex in forty-one studies which employed various brain imaging techniques and 16,771 participants in total (Figure 4; Lam et al., 2021).

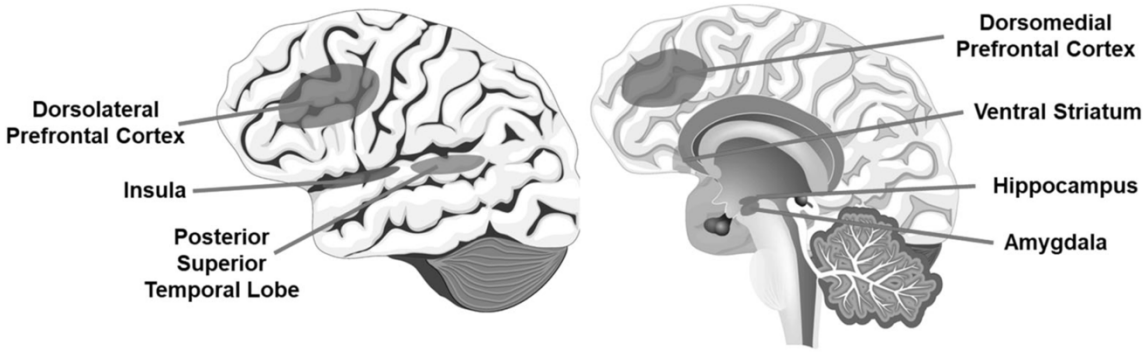


Figure 4. Summary of the Brain Structures Consistently Implicated in Loneliness (Lam et al., 2021)

As illustrated in Figure 5, chronic loneliness disrupts the core neural substrates of cognitive, emotional, and sensory processes, resulting in negative cognitive biases, impaired memory and working memory, altered reward-related responses, and heightened sensitivity in sensory processing (Lam et al., 2021). This is driven by changes in specific neural regions such as the amygdala, prefrontal cortex, insular cortex, and ventral striatum (Morr et al., 2022a). This theoretical model also reported the impact of situational and chronic loneliness on cognitive, emotional, and sensory processes (Morr et al., 2022a).

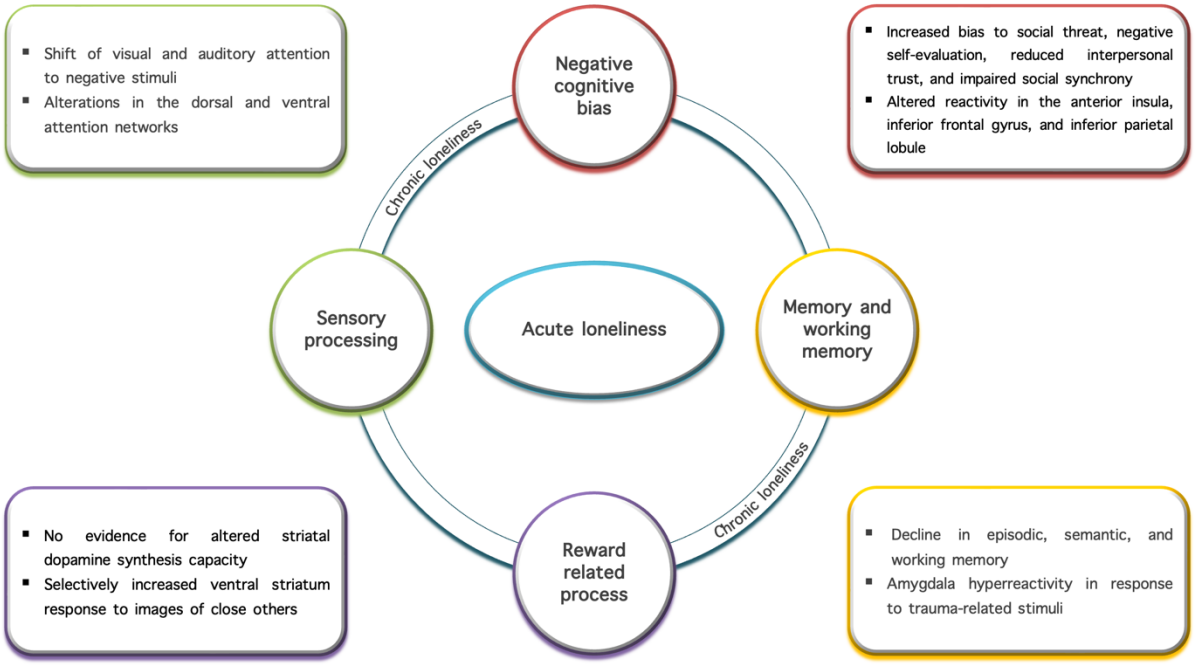


Figure 5. Theoretical Model Illustrating the Impact of Acute and Chronic Loneliness on Cognitive, Emotional, and Sensory Processes (adapted from Morr et al., 2022a)

2.2.1. Amygdala: Emotion Processing and Social Threat Perception

Amygdala is widely recognised as the central hub for processing social threat surveillance, such as fear-related cues and aversion and has consistently been reported to be hyperactive in lonely individuals (Morr et al., 2022a; Vitale & Smith, 2022; Cacioppo & Cacioppo, 2015). It is known to intensify negative emotions like fear and anger, which helps to prioritise attention to socially threatening stimuli and is considered to contribute to a bottom-up attentional bias during the visual processing of facial emotions (Weidner et al., 2024). Further evidence from Berhe et al. (2023) linked this reduced amygdala habituation to more negative perceptions of social interactions and a greater preference for being alone.

Moreover, previous studies found that there is a positive correlation between amygdala volume and social distress, which is significantly mediated by loneliness

(Tian, 2016; Lieberz et al., 2021). In a systematic review by Lam et al. (2021), loneliness has been associated with structural and functional alterations in amygdala with possible age- and sex interactions. In conclusion, these findings highlight that the feeling of loneliness is reflected in amygdala activity, connectivity, and volume, which impact social threat perception and emotion processing, consequently affecting the evaluation of social interactions.

2.2.2. The Prefrontal Cortex: Cognitive Control, Emotion Regulation and Social Functioning

The prefrontal cortex (PFC), particularly the ventromedial and dorsolateral areas, plays a critical role in modulating emotions by downregulating activity in the amygdala, which consequently reduces emotional reactivity (Lam et al., 2021; Etkin et al., 2011). It integrates sensory and emotional information to support decision-making and regulate responses to social situations (Amodio & Frith, 2006). Hence, it is suggested that the hyperactivity in the amygdala leads to reduced response and connectivity with the dorsal prefrontal cortex in the early stages of information processing, which possibly contributes to maladaptive social behaviours, such as withdrawal or negative interpretations of social cues (Cacioppo & Cacioppo, 2015). PFC has also been reported to play a central role in cognitive control, which allows people to evaluate social cues by monitoring the current situation, prioritising the relevant information, and ultimately determining appropriate social behaviour with optimal actions (Doheny & Lighthall, 2023; Adolphs, 2010). In conclusion, the role of PFC in cognitive control and emotion regulation functions is essential for advanced social ability, and reduced activation in this region contributes to difficulties in social functioning and leads to an inability to detect social and emotional cues accurately.

2.2.3. The Insular Cortex: Interoceptive and Exteroceptive Processing

Recent literature highlighted that the PFC and insular cortex (IC) work in tandem to regulate adaptive emotional and social processes (Barton et al., 2024; Weiner et al., 2024). Insula is a key brain region in processing both interoceptive (emotional awareness) and exteroceptive (social cognition) information (Zhang et al., 2024). Cacioppo et al. (2009) reported that reduced insula activity was observed among lonely individuals while processing pleasant social stimuli. In another study done by Eisenberger (2012), where social rejection was experimentally induced by a virtual ball-tossing game, the insula activity was increased.

Recently, Vitale and Smith (2022) illustrated how the brain processes social and emotional cues through a predictive coding framework (Figure 6). They proposed that prediction neurons, localised in the agranular cortex of the insular cortex (responsible for forming expectations based on past experiences) send strong predictive signals to dysgranular and granular layers. Simultaneously, the brain gives greater attention to negative social cues that match these predictions (e.g., social rejection) and disregards cues that do not match, such as positive or neutral social cues. As a result, prediction-error neurons fail to activate sufficiently, preventing the necessity to update the predictive model of the brain, meaning the brain does not receive the feedback to realise its predictions were wrong so it can adjust its thinking. Consequently, this mechanism might produce a negative cognitive bias, potentially reinforcing maladaptive emotional and social processes and perpetuating loneliness.

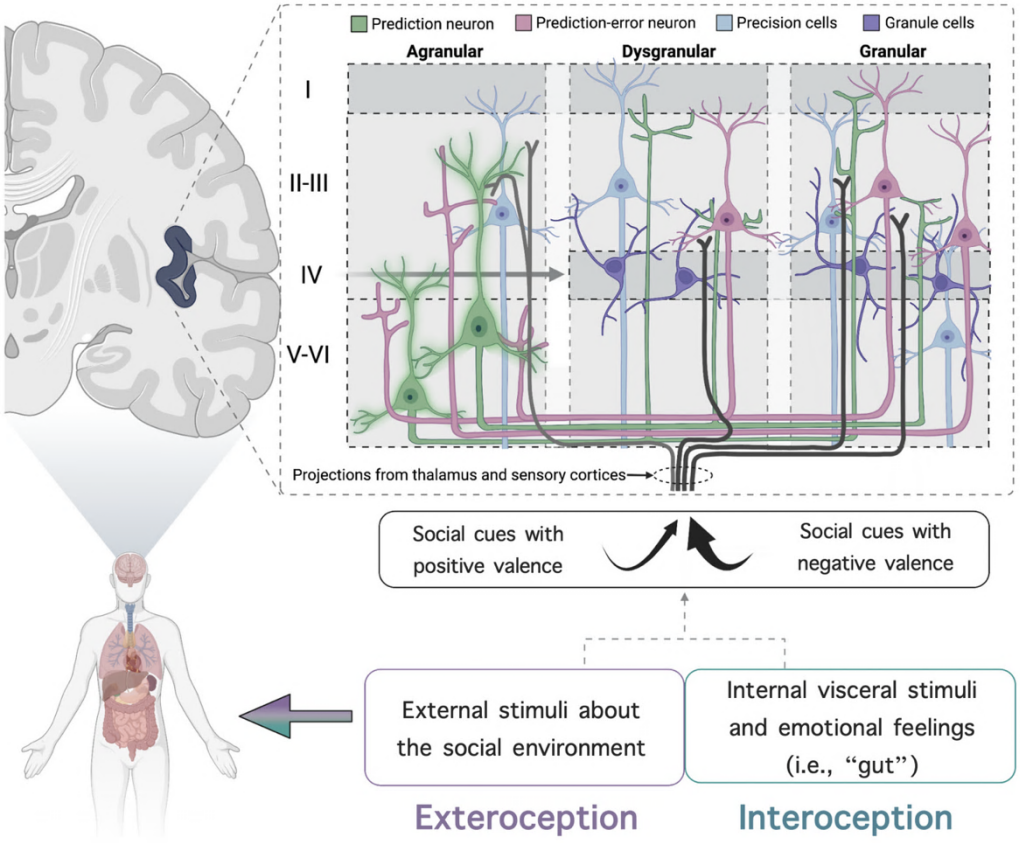


Figure 6. Schematic of Proposed Insular Cortex Activity in Lonely Individuals (Vitale et al., 2022)

2.2.4 Ventral Striatum: Reward Processing and Motivation for Social Connections

Previous research suggests that loneliness is associated with appetitive social information processing (Cacioppo, 2014). The ventral striatum, a key component of the mesolimbic dopamine system which is crucial in reward processing and motivation, is typically activated by both primary and secondary rewards (such as stimulant drugs and money; Leyton, 2007; Seymour et al., 2005) and social rewards (such as sexual desire and love, social cooperation and social; Lieberz et al., 2022).

However, Cacioppo et el. (2009) reported that lonely individuals demonstrated stronger ventral striatum activation to pleasant non-social stimuli (e.g., objects) compared to pleasant social stimuli (e.g., people). In contrast, non-lonely individuals

demonstrated greater activation to pleasant pictures of people than of objects (Inagaki et al., 2016). A recent meta-analysis by Wong et al. (2022) supported these findings suggesting that lonely individuals showed increased activations in the striatum while processing negative emotional stimuli. These findings suggest that loneliness may disrupt the reward and motivation system in the brain, leading to a diminished response to positive social interactions and a preference for non-social rewards, which could potentially further reinforce social withdrawal and isolation.

Overall, reduced volume and heightened activation in amygdala (Lam et al., 2021; Düzel et al., 2019), reduced volume and activation in PFC (Kiesow et al., 2020); alterations in the insular cortex (Finley & Schaefer, 2022); reduced volume and alterations in ventral striatum (Franco-O'Byrne et al., 2023; Uddin et al., 2017) among lonely individuals underpin the maladaptive characteristics of loneliness leading to reduced social affiliation and increased aversion, negative cognitive biases, emotion dysregulation (high social pain), and impaired social cognition (Franco-O'Byrne et al., 2023). Together, these findings underscore the importance of how loneliness disrupts key neural circuits, perpetuating maladaptive emotional, cognitive, and social processes.

2.3. The Cognitive Perspectives on Loneliness

Loneliness has been a focus of various theoretical models seeking to explain its origins, maintenance and how it might affect the cognitive processes of individuals. While the “Cognitive Discrepancy Model” explained by Peplau and Perlman (1982) emphasises the role of the perceived gap between actual and desired interpersonal relationships and how cognitive attributions shape an individual's interpretation of

social interactions, the "Cognitive-Behavioural Model" by Käll et al. (2020) explores the self-reinforcing cycle of loneliness, where maladaptive thoughts, emotions, and behaviours interact to perpetuate loneliness. This thesis focuses on cognitive biases as a core area of investigation, which are central to cognitive frameworks.

2.3.1. The Cognitive Discrepancy Theory of Loneliness

Peplau & Perlman (1982) proposed "The Cognitive Discrepancy Model" which proposes that cognitive processes are the key element in understanding loneliness (Figure 7). This approach posits that while loneliness results from a subjective discrepancy between one's existing (perceived) and desired relationships, cognitive processes and attributing causality also impact lonely individuals' interpretation of social information (Russell et al., 2012). According to this model, social interactions are impaired by irrational or distorted thought patterns which contribute to loneliness. Building on "Attribution Theory" (Fiske & Taylor, 1979), the model further suggests that "*while lonely individuals attempt to explain the causes of their own and other people's behaviours, they attribute causality in specific ways"* (Murphy & Kupshik, 1992, *p. 7*). For example, lonely individuals are more likely to make internal attributions (Caglar & Deniz, 2024) and believe that their loneliness is due to their personality (e.g., being inherently uninteresting, unchangeable personality traits, fear of rejection, self-doubt, social anxiety; Hemberg et al., 2021; Borawski et al., 2022) and high expectations for interpersonal relationships (Harper et al., 2020). Consequently, lonely individuals may withdraw from social opportunities that are available because of the expectations of rejection, unrealistic standards for potential relationships, and the belief that no one "measures up" (Visvalingam et al., 2024; Jones & Sharpe, 2017; Rook & Peplau, 1982).

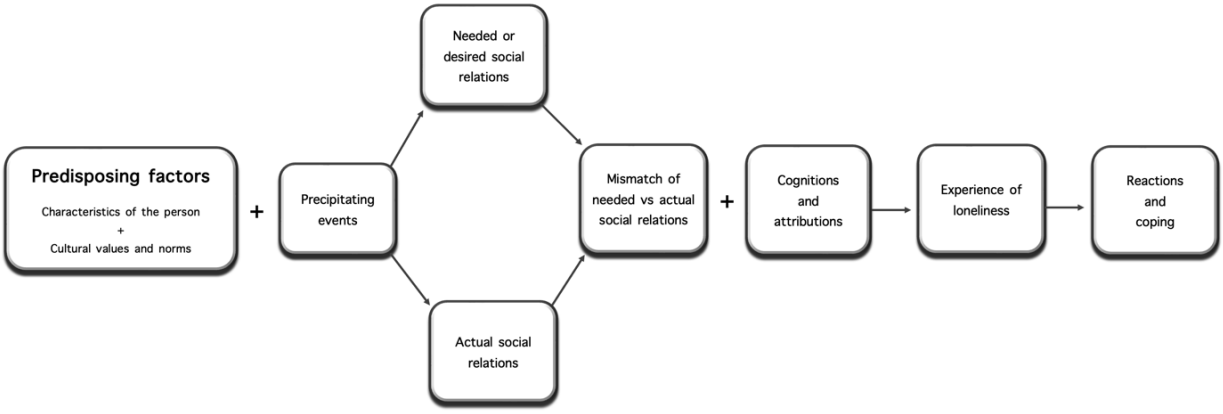


Figure 7. The Cognitive Discrepancy Theory of Loneliness (adapted from Perlman & Peplau, 1982)

2.3.2. The Cognitive-Behavioural Model of Loneliness

Käll et al. (2020) developed a model of maintenance for chronic loneliness resulting from three main factors: (a) self-focused attention, (b) avoidance, and (c) counterproductive behaviour (Figure 8). This model conceptualises thoughts, emotions, and behaviours through a self-reinforcing cycle. According to this model, loneliness begins with an interpersonal trigger or context, such as a situation in which an individual feels their relationships are unsatisfactory in comparison to what one values. This discrepancy then leads to negative interpersonal appraisals that produce counterproductive behaviours, such as social withdrawal, or strong emotional reactions such as fear, anxiety, and depression. While the counterproductive behaviours can lead to a decrease in connections, often exacerbated by personal challenges, such as social skills deficits, the intense emotions triggering cognitive distortions, such as hypervigilance to potential rejection, making social interactions feel more threatening. Over time, this decline in connection perpetuates the cycle of loneliness. Therefore, this cognitive-behavioural framework emphasises the importance of addressing cognitive biases as it is seen as a starting point of this cycle.

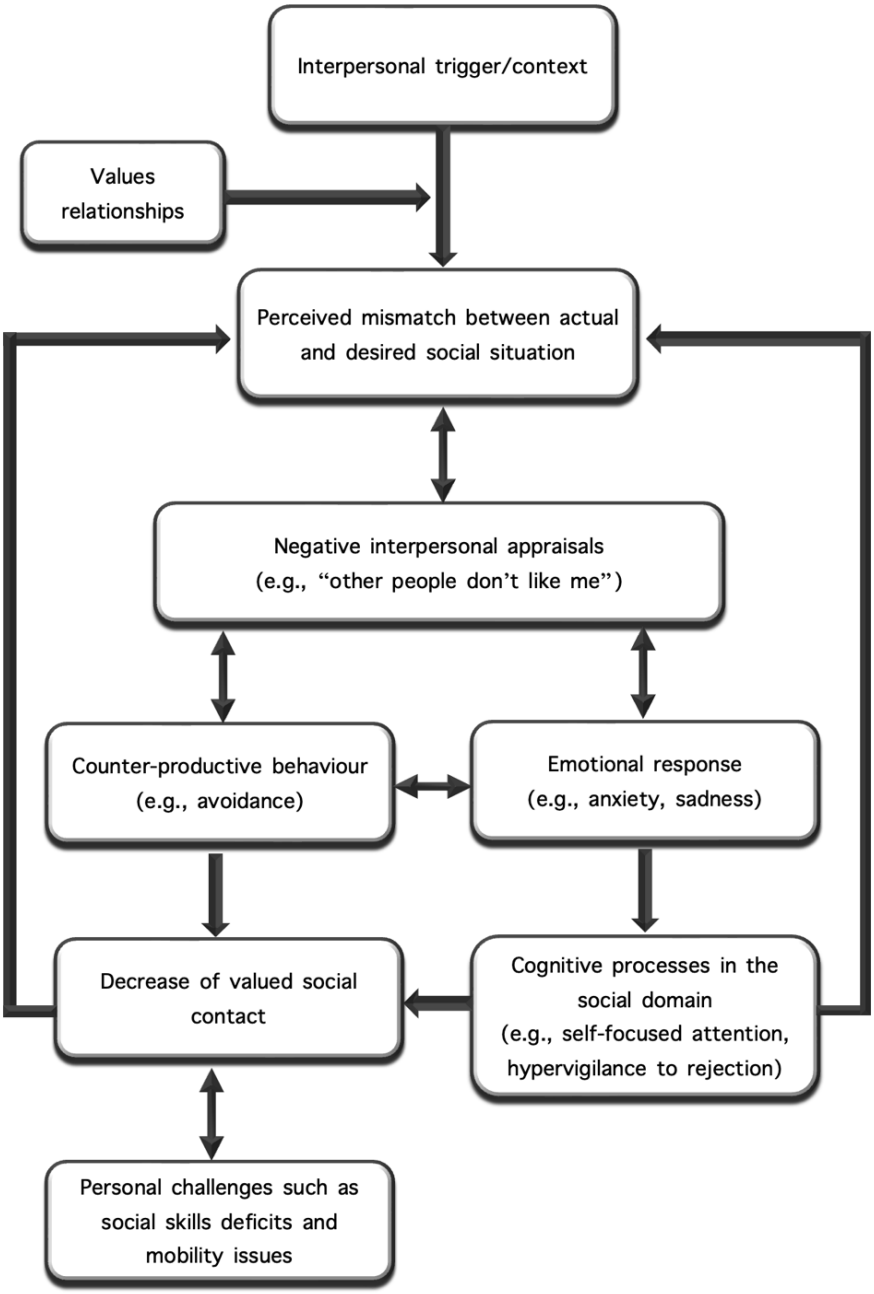


Figure 8. A Cognitive-Behavioural Analysis of the Maintenance of Chronic Loneliness (adapted from Käll et al., 2020)

2.3.3. Cognitive Biases in Loneliness

Humans see the world through the lens of evolved adaptations (Buss, 2005). According to the evolutionary perspective, cognitive biases arise from heuristics that evolved to address survival needs and respond adaptively ('evolutionary rationality'; Haselton & Nettle, 2006). Cognitive biases are systematic, pervasive, and persistent

cognitive distortions which occur when the human brain relies on mental shortcuts, or heuristics, to interpret and respond to social cues (Korteling et al., 2018; Korteling et al., 2023; Tversky & Kahneman, 1974). In clinical context, cognitive biases have been widely investigated in relation to mental health conditions such as depression (Quigley et al., 2022; Nieto et al., 2020), anxiety (Lange et al., 2012; Rinck et al., 2013), and obsessive-compulsive disorder (OCD; Hezel et al., 2016).

As mentioned in previous section, although hypervigilance was once advantageous for detecting and reacting to social threats for survival, they might now contribute to distorted perceptions of social cues, which are maladaptive in modern social environments, reinforcing social withdrawal and limiting opportunities for connection. Loneliness initially leads people to social withdrawal to allow effective observation and evaluation of their current social environment through physical distancing (Qualter et al., 2015). In the meantime, this process triggers a series of cognitive mechanisms to generate behavioural responses to reconnect with others (Cacioppo & Hawkley, 2009; Qualter et al., 2015). These cognitive mechanisms prioritise the processing of social information over non-social information, allowing individuals to react more quickly to social cues that signal opportunities for reconnection or the risk of further social isolation (Cacioppo & Hawkley, 2009). As a result, lonely individuals may develop a self-preservation-focused cognitive bias that overemphasises social isolation cues while neglecting social cues to protect themselves against socially threatening situations. Consequently, this cognitive bias leads to self-defeating behaviours in non-threatening environments and perpetuates their loneliness (Cacioppo & Hawkley, 2009; Qualter et al., 2015).

Spithoven et al. (2017) published a comprehensive review examining the empirical evidence for these cognitive aspects of loneliness using the "Social Information Processing" (SIP) model (Crick & Dodge, 1994). According to this model, the cognitive process involves four steps: *attending and decoding the cue, interpreting the cue, determining the behavioural response and enacting the chosen response* (Crick & Dodge, 1994). Spithoven et al. (2017) proposed that while individuals generally employ the same cognitive processes, lonely individuals demonstrate cognitive biases at various stages of these processes. Therefore, the primary focus of this thesis is three main cognitive biases: *attention, interpretation, and approach-avoidance biases*, which play pivotal roles in shaping social perceptions and interactions of lonely individuals.

Attention bias refers to the tendency to focus attention on certain cues over others (Spithoven et al., 2017). In the context of loneliness, individuals may exhibit hypervigilance towards negative social cues, such as negative facial emotions, perceived rejection or hostility, while overlooking positive cues. This selective attention can reinforce feelings of social disconnection. Meanwhile, *interpretation bias* refers to attributing neutral or ambiguous social cues negatively (Grocott et al., 2024; Morningstar et al., 2020; Lau et al., 2021). For instance, lonely individuals might perceive neutral interactions as dismissive or judgmental, exacerbating their sense of isolation (Nombro et al., 2022). Finally, building upon Cacioppo and Hawkley's (2009) model of loneliness, which was recently expanded by Qualter et al. (2015), and Spithoven et al.'s (2017) comprehensive review of cognitive aspects of loneliness within the SIP model, this thesis expands the scope by investigating approach-avoidance bias along with the attention and interpretation biases. *Approach-avoidance* bias refers to the conflicting motivations to engage in or withdraw from social interactions (Loijen et al., 2020) and

is conceptually aligned with the initial withdrawal reaction of lonely individuals through physical distancing, as described in the aforementioned models. Previous research posits that individuals with repressive coping styles demonstrate avoidance of positive social cues, which may impair social engagement and consequently contribute to feelings of loneliness (Maitland, 2020; Layden et al., 2018; Gable, 2008). Although approach-avoidance bias received limited attention in the literature, recognising its critical role in the complex behavioural dynamics of loneliness is essential.

Overall, these cognitive biases operate within the framework of social information processing, shaping how lonely individuals perceive, attend, process, interpret, and react to social and emotional cues. Understanding these biases is crucial, as they may perpetuate self-reinforcing cycles that maintain or exacerbate loneliness.

2.4. The Social Theories of Loneliness

Loneliness often arises from changes in a person's social relationships that result in a sub-optimal level of achieved social relationships, and these changes may impact a single relationship or the entire social network (Perlman & Peplau, 1982). Despite the pervasiveness and importance of the loneliness phenomenon, social scientists have attempted to study it only recently in a social context. Although loneliness is often perceived as a personal emotional experience, it is deeply rooted in social contexts and shaped by the structures and interactions of social networks (Borgatti & Ofem, 2010). Therefore, this section explores two prominent complementary social theories: “Social Network Theory” (SNT) and “Social Safety Theory” (SST). These theories provide a comprehensive approach to our understanding of how individual experiences of loneliness interact with larger social structures influencing the spread and impact of

loneliness across communities and how social safety explains behavioural responses to loneliness.

2.4.1. Social Network Theory in Loneliness

Weiss (1975, *p.15*) proposed that *"loneliness is the lack of integration into a social network"*. The Social Network Theory (SNT) relies on Moreno's *sociometry*, which is described as *"the mathematical study of psychological properties of populations, the experimental technique and the results obtained by application of quantitative methods"* (Moreno, 1937, *p.307*). SNT examines relationships across ego-centric, socio-centric, and open-system networks, emphasising that connections are influenced by four main factors. They include (a) *proximity* (propinquity; e.g., people are more likely to form connections when geographically or socially close); (b) *shared attributes* (homophily; e.g., connections are stronger when individuals share similar attributes); (c) *the balancing of mutual ties* (triads and balance; e.g., relationships tend to balance over time; mutual friends reinforce networks); and (d) *core-periphery clusters with weaker ties at the periphery* (e.g., stronger, denser networks form in the core, while peripheral nodes have weaker connections; Kadushin, 2004). In the context of loneliness, little is known about the placement of loneliness within, or the spread of loneliness through social networks.

Cacioppo et al. (2009) published a longitudinal observational cohort study investigating the dynamics of loneliness within social networks using data from 12,067 individuals derived from the Framingham Heart Study (FHS; Figure 9). They reported that loneliness spreads contagiously through social networks up to three degrees of separation. At *the first degree*, people are 52% more likely to be lonely if someone they are directly connected to is lonely. At *the second degree*, a person is 25% more likely to

be lonely if a friend's friend (a person indirectly connected) is lonely. At *the third degree*, a person is 15% more likely to be lonely if a friend's friend's friend (further indirect connection) is lonely. The findings further suggested that loneliness is both individual and collective, which influences not only the lonely person but also their social ties and spreads more through friendships than family ties, especially among women than men.

Moreover, lonely individuals are more likely to be surrounded by others who are also lonely, forming identifiable "*loneliness clusters*", and they are more likely to lose social ties over time (Cacioppo et al., 2009). They also suggested that physical closeness amplifies the spread of loneliness, meaning friends and neighbours living closer to one another exert a stronger influence on loneliness compared to those farther away. Overall, loneliness is a contagious social phenomenon that spreads through social networks.

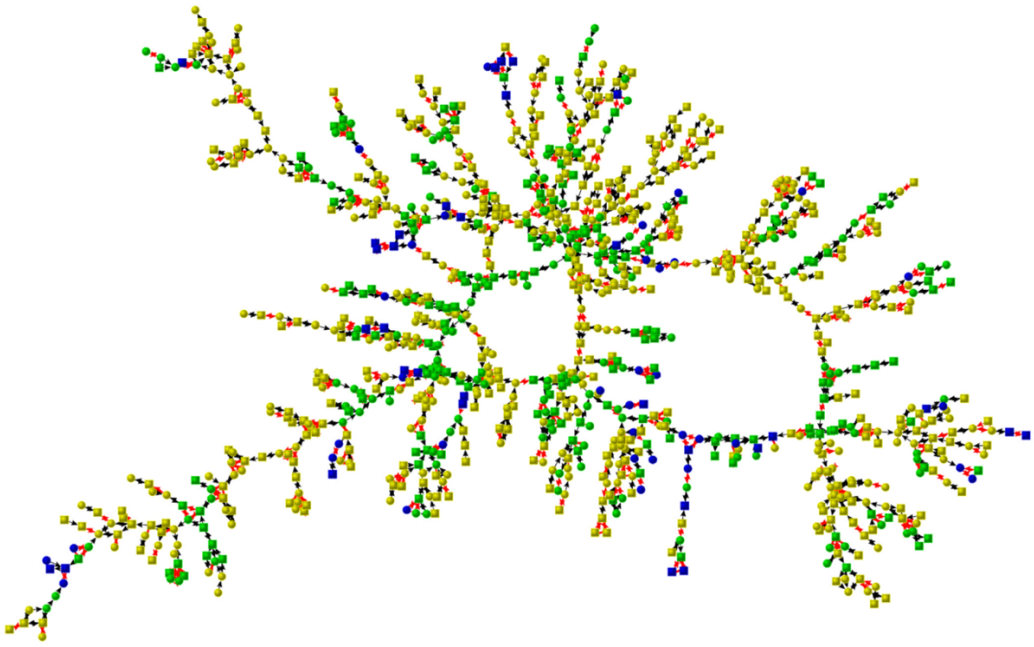


Figure 9. Loneliness Clusters in the Framingham Social Network (retrieved from Cacioppo et al., 2009)

Note: Figure 9 displays 1,019 individuals, with each node representing a person in the largest connected component of the friendship, spousal, and sibling network. Node shape denotes gender (circles = female; squares = male). Edges indicate relationship type (red = siblings; black = friends and spouses). Node colour represents the mean number of days the focal person and their directly connected network members (linked persons at distance 1) reported feeling lonely during the past week (yellow = 0–1 days; green = 2 days; blue = ≥3 days). The figure illustrates clustering of loneliness within the network and an association between network peripherality and loneliness, which are formally tested in the statistical models described in the main text.

2.4.2. Social Safety Theory

Social Safety Theory (SST; Slavich, 2020) has not been specifically developed for loneliness; however, it provides a theoretical framework for the behavioural responses to loneliness. SST suggests that perceiving social threats activates a specific immune response that is designed to prepare human beings for physical injuries, which is more likely to happen when a social animal is separated from its group (Slavich, 2022). Meanwhile, it reduces its defences against viral infections, which are less likely to happen when isolated from a social group. If this inflammatory reaction is chronic, it disrupts physical and mental health (Slavich, 2020). This behavioural adaptation, in fact, may involve safety behaviours, which are cognitive or behavioural strategies to avoid social situations or decrease the possibility of perceived threat (Patel et al., 2024; Cougle et al., 2020). These safety behaviours (e.g., such as avoiding eye contact or social events, excessively monitoring others, behaviours during social interactions) are closely linked to cognitive biases, especially approach-avoidance bias, in which a person keeps a distance from others because of perceived social context as unsafe or threatening (Best et al., 2021). Thus, SST offers a foundation to explore how loneliness may drive not only physiological changes but also maladaptive behaviours that perpetuate loneliness.

3. Risk Factors for Loneliness

3.1. Biological Risk Factors

3.1.1. Genetic and Neurobiological Underpinnings

Behavioural genetic analyses across the lifespan have demonstrated that loneliness is in part heritable (Cacioppo et al., 2015; Goossens et al., 2015; Boomsma et al., 2005). Genetic factors accounted for 23.26% of the total variance in loneliness in a study with

3,066 twins from the USA (Moshtael et al., 2024); 37% of variance in a study with 2,232 twins from the UK (Matthews et al., 2016); 42% variations in a study with 7,477 twins from the Netherlands (Vinkhuyzen et al., 2012); 48% variations in another study from the Netherlands with 8,387 twins (Boomsma et al., 2005); and 35% variations in a study with 1,210 twins from Japan (Ando et al., 2019); Recurring key genetic pathways associated with loneliness across studies include OXTR (oxytocin receptor for social bonding regulation); DRD2/DRD4 (dopamine receptors for social reward-seeking motivation); SLC6A4 (serotonin transporter for mood and resilience); NR3C1 (glucocorticoid receptor for stress response adaptation) and inflammatory markers such as IL-6 (interleukin-6 for inflammation and stress; Abdellaoui et al., 2018, 2019a, 2019b; Bartels et al., 2008; Boomsma et al., 2005; Bowirrat et al., 2023; Cacioppo et al., 2018b; Gao et al., 2017; Matthews et al., 2016; Moshtael et al., 2024; Schermer et al., 2023).

Accumulating evidence in the literature suggests that loneliness is associated with structural and functional differences in the prefrontal cortex (PFC), anterior cingulate cortex (ACC), insula, hippocampus, and amygdala (Dabiri et al., 2024; Morr et al., 2022b; Lam et al., 2021; Cacioppo et al., 2014). Brain regions critical for emotional regulation, social processing and memory have been also linked to loneliness, such as functional disruptions in the default mode network (DMN), which mediates self-referential thought and social processing (Lam et al., 2021; Bowirrat et al., 2023) and reductions in grey matter in the dorsolateral PFC and hippocampus (Dabiri et al., 2024; Bowirrat et al., 2023). Moreover, grey and white matter volumes have also been found to be lower in the insula and PFC in lonely individuals (Nakagawa et al., 2015; Düzel et al., 2019). Loneliness also correlates negatively with grey matter density in the left posterior superior temporal sulcus (pSTS), which is involved in biological motion and social

perception (Kanai et al., 2012). Additionally, the dorsomedial prefrontal cortex (dmPFC) has also been shown to play a role in loneliness (Power et al., 2018). These findings underscore the profound impact of structural and functional brain alterations on loneliness, highlighting the neurobiological underpinnings of loneliness.

3.1.2. Neuroendocrine and Inflammatory Dysregulations

Neuroendocrine and inflammatory dysregulation functions act as risk factors for loneliness by increasing stress reactivity, reducing social motivation, and impairing emotional and immune system regulation. Loneliness has been linked to hypothalamic-pituitary-adrenal (HPA) axis dysregulation, resulting in elevated cortisol levels and disrupted diurnal rhythms (Hackett et al., 2012; Zilioli & Jiang, 2021). The elevated cortisol levels intensify stress sensitivity and reduce adaptive coping, causing hypervigilance to social threats and making individuals more sensitive to perceived social threats (Cacioppo et al., 2015). Simultaneously, loneliness was also associated with a proinflammatory state characterised by elevated levels of interleukin-6 (IL-6) and C-reactive protein (CRP), immune dysfunction and glucocorticoid resistance (Hackett et al., 2012; Pourriyahi et al., 2021; Zilioli & Jiang, 2021). These inflammatory responses not only increase physical health risks but also disrupt brain regions like the PFC and hippocampus, further impairing social motivation and emotional resilience (Ahmed et al., 2023; Vitale et al., 2022). Loneliness and these physiological dysregulations are deeply intertwined in a bidirectional relationship where neuroendocrine and inflammatory changes heighten vulnerability to loneliness, while chronic loneliness reinforces these physiological alterations, creating a self-perpetuating loop (Jaremka et al., 2013; Balter et al., 2019).

3.2. Psychological Risk factors

3.2.1. Attachment Styles

"Attachment Theory", originally introduced by Bowlby (1979), describes an innate system motivating humans to seek connection and support from an attachment figure, particularly during periods of threat or uncertainty (Ainsworth & Bowlby, 1991). Building upon Bowlby's theory, contemporary perspectives emphasise three primary attachment styles: (a) *secure attachment*, which is associated with trust in others and resilience in navigating social interactions (Kordoutis & Moschos, 2024; Hutten et al., 2021a); (b) *anxious (or anxious-ambivalent) attachment* which is characterised by heightened sensitivity to rejection and hypervigilance toward relational threats (Borawski et al., 2021; Benoit & DiTommaso, 2020); and (c) *avoidant attachment (both fearful and dismissive)* which is associated with emotional and physical distancing (Kaitz et al., 2004).

While secure attachment has been consistently negatively correlated with loneliness, fostering emotional resilience, increasing relationship quality, and acting as a protective factor (Benoit & DiTommaso, 2020); insecure attachment styles, *both anxious and avoidant*, have been found to contribute to loneliness through emotional dysregulation, impaired social skills, low self-esteem, emotional vulnerability and interpersonal difficulties (Kordutis & Moschos, 2024; Borawski et al., 2022). Individuals with anxious attachment often experience loneliness due to their intense need for validation, fear of rejection and abandonment, while individuals with avoidant attachment are more likely to feel lonely due to their emotional detachment and reluctance to rely on others (Mikulincer et al., 2021; Wildschut et al., 2011). These

findings highlight the lasting effect of insecure attachment styles on interpersonal relationships across the lifespan.

3.2.2. Mental Health Problems

Mental health problems significantly contribute to loneliness, creating a complex and often cyclical relationship where one exacerbates the other (Sparks et al., 2024; Qualter et al., 2022). A comprehensive systematic review including longitudinal studies on the impact of mental health problems on loneliness and perceived social support documented that loneliness is associated with a range of mental health problems such as depression, anxiety, schizophrenia and schizoaffective disorders (Wang et al., 2018a). There is also accumulative evidence in the literature reporting the association between loneliness and neuroticism, extraversion, conscientiousness, alexithymia, and personality traits (Lieberz et al., 2022; Abdellaoui et al., 2019a; Hards et al., 2022; Schermer & Martin, 2019; Stein & Tuval-Mashiach, 2015). These traits may predispose individuals more susceptible to loneliness by increasing their sensitivity to social rejection, hindering their ability to express and understand emotions effectively, reducing their motivation to engage in social interactions, and distorting their perceptions of social relationships (Porter & Chambless, 2016; Mann et al., 2021).

The bidirectional relationship between loneliness and mental health problems is compounded by stigma, which can act as both a barrier to seeking support and a trigger for further social withdrawal and isolation (Qualter et al., 2022; Pitman et al., 2018). Therefore, understanding and addressing loneliness as both a risk factor and a consequence of mental health problems is crucial.

3.2.3. Personality Traits

Personality traits play a crucial role in shaping the susceptibility of individuals to loneliness through their impact on social behaviour and relationship formation (Back et al., 2023). Previous literature, both cross-sectional and longitudinal studies, consistently demonstrated that certain personality traits are associated with loneliness, which influences both social perceptions and interactions of lonely individuals (Erevik et al., 2023; Buecker et al., 2020). A robust body of research documented a wide range of personality traits within the Big Five framework, while neuroticism was reported to be positively related to loneliness, and extraversion, agreeableness, conscientiousness, and openness were negatively related to loneliness (Shrestha et al., 2024; Buecker et al., 2020; Wang et al., 2018b).

For instance, a higher level of neuroticism might predispose individuals to perceive emotional and social cues as threatening or unsatisfying, as it heightens emotional reactivity to social stressors and social rejection (Lieberz et al., 2022; Abdellaoui et al., 2019a). Beyond the Big Five traits, psychopathological traits such as negative affectivity, detachment, and antagonism, as described in the DSM-5 Alternative Model for Personality Disorders (AMPD), also have a strong impact on loneliness (Freilich et al., 2022; Reinhard et al., 2022).

3.3. Sociocultural Risk Factors

3.3.1. Sociocultural Determinants of Loneliness

a. Individualism vs Collectivism: The experience and prevalence of loneliness are significantly affected by the cultural constructs. While *individualism* is characterised by an emphasis on autonomy, personal goals, and self-expression, fostering loose social

networks based on personal choice (Dahlberg, 2024); *collectivism* refers to interdependence, family, and community relationships, resulting in tightly knit social networks based on obligations and shared identity (Hofstede, 2011). Traditional perspectives suggest that individualistic societies foster a higher prevalence of loneliness because of the prioritisation of personal autonomy over communal ties (Rokach, 2005; Holt-Lunstad et al., 2010). While some recent research supports this viewpoint, others contradict it with conflicting results. For instance, Barreto et al. (2021) analysed the frequency of loneliness reported by 46,054 participants between 16 and 99 years old across 237 countries representing both individualistic and collectivistic cultures and found that loneliness increased with individualism. Similarly, Heu et al. (2019) found that higher individualism was related to higher loneliness, whereas higher collectivism was associated with lower loneliness in their study of five European countries. However, Swader (2019) reported that societal individualism was associated with lower loneliness, even when considering the partial mediating role of social isolation in this relationship. This suggests that individuals might report higher levels of social isolation, but that does not necessarily mean higher levels of perceived loneliness.

Further evidence from Schermer et al. (2023), based on data from 8,345 people across 28 countries, revealed that horizontal individualism and collectivism were both associated with lower levels of loneliness. Similarly, according to Eskin et al. (2020), young adults in both individualistic and collectivistic societies report similar experiences of loneliness, suggesting that modern social challenges may be converging across cultural contexts.

Moreover, recent studies highlight how globalisation and technological advancements are blurring the traditional individualistic-collectivistic distinctions,

creating new forms of loneliness that transcend cultural boundaries (Abdelrahim & Frank, 2024; Yeganeh, 2024). Luhmann et al. (2023) contributed to this discussion by suggesting that loneliness might be more prevalent in individualistic societies because people might invest less in social relationships, whereas loneliness in collectivistic societies may stem from a perception that their existing social connections are inadequate because social ties are more important for collectivist individuals. In conclusion, it is still not clear which cultural group has higher levels of loneliness; however, it is evident that cultural factors significantly influence the way loneliness is experienced.

b. Urbanisation: In contemporary societies, *urbanisation* serves as a significant risk factor leading to loneliness. According to the EU Loneliness Survey (Eurostat, 2023), people living in very rural areas are not only more likely to be socially isolated but also more at risk of feeling lonely (Zimmermann et al., 2024). But at the same time, the experience of loneliness appears to increase with population density. Recent research suggests that urban cities, despite their population density and offering proximity to others, can paradoxically foster loneliness. For instance, Lai et al. (2021) analysed data from UK Biobank, a cohort of 478,265 adults aged 37–73 years recruited between 2006 and 2010 and found that people living in high-density urban areas reported higher levels of loneliness compared to those living in suburban or rural areas. It was proposed that urbanisation diminishes chances for substantial social interactions and leads to looser community bonds, which may increase social stress. Chen and Gong (2022) also reported that urban residents increasingly rely on digital communications at the expense of face-to-face interactions, potentially exacerbating feelings of loneliness.

c. *Migration:* According to literature, *migration* is also a key factor contributing to loneliness in urban areas, as urban centres often attract transient populations like migrants who face difficulties in establishing long-term connections (Franklin et al., 2021). As a result, migration, whether it is international or internal, adds complexity to social integration, presenting distinct challenges in building meaningful relationships and nurturing a sense of belonging, which can heighten feelings of isolation (Koelet & de Valk, 2016). In a recent comprehensive scoping review analysing 76 studies, Joshi et al. (2024) reported that migration leads to a loss of pre-existing social connections, with migrants struggling to rebuild networks in their host countries due to barriers such as language and cultural differences, racism, discrimination, marginalisation, inadequate housing, limited access to healthcare which constrain social participation and contribute to isolation (Koehn et al., 2022; Fokkema & Ciobanu, 2021).

Overall, the intersection of urbanisation and migration presents unique challenges that lead to loneliness in contemporary societies by shaping social structure and how individuals connect.

3.3.2. Demographic Risk Factors

a. *Age: Age* emerges as a significant risk factor for loneliness, often outweighing other variables, such as gender and ethnicity (Shovestul et al., 2020). However, when age-related factors are considered, the relationship between age and loneliness becomes more complex and nonlinear, with distinct patterns and contributing factors at different stages of life (Hawkley et al., 2022; Shovestul et al., 2020). Each phase presents unique vulnerabilities and challenges that shape the experience of loneliness. In childhood and adolescence, loneliness often stems from developmental vulnerabilities (e.g., cognitive

immaturity, developing emotion regulation skills, identity uncertainty), the instability of their social network like changes in school, heightened need for peer acceptance, as well as identity formation, and physical changes, which make them vulnerable to exclusion (Barreto et al., 2021; Qualter et al., 2013).

Therefore, particularly adolescents face the dual pressures between the need for social connection (the need for belonging) and individuation (the need for independence), which heightens their susceptibility to loneliness (Qualter et al., 2015). In young adulthood, transitional stressors, such as leaving home, building new relationships, starting careers, moving to a new city or country and loss of social connections emerge (Hawkley et al., 2022; Franssen et al., 2020). These life changes can disrupt social connections and contribute to the experience of loneliness. In middle age, loneliness is often influenced by the efforts to balance work, family, and social roles, work-related stress, caregiving responsibilities, separation, and reduced time availability due to work (Luhmann & Hawkley, 2016). In older age, retirement, social losses (e.g., widowhood), living alone, bereavement and reduced mobility can shrink social networks and limit opportunities for meaningful interactions, increasing vulnerability (Hawkley et al., 2022; Barreto et al., 2024; Luhmann & Hawkley, 2016). Therefore, different age groups experience specific challenges contributing to loneliness (Jopling & Sserwanja, 2016; Heckhausen et al., 2010). While those might be universal, others might stem from other variables, such as culture (Yang & Victor, 2011).

b. Gender: It has been proposed that women and men are different in terms of how they socialise and what type of emotional needs these relationships are expected to meet (Chodorow, 1978). *Gender differences* in loneliness are well-documented, but the findings reveal complexities influenced by factors such as cultural factors, life stages, and social

expectations, hence, the association between loneliness and gender remains inconclusive. Some research documented that women often report higher levels of loneliness compared to men; however, men might experience it more intensely because of a lack of emotional openness and smaller social networks (Rokach, 2018; Victor & Yang, 2012).

A meta-analysis by Maes et al. (2019) examined gender differences in loneliness across the lifespan by analysing data from 399,798 individuals and concluded that the overall gender difference in loneliness was close to zero, with a small but significant effect indicating that men are slightly lonelier than women. However, a recent 15-year longitudinal study with 2,315 people aged between 40 and 80 years old by Nicolaisen and Thorsen (2024) demonstrated that women consistently reported higher levels of loneliness than men due to several factors such as partner loss, mental health, and age-related changes playing key roles in shaping gendered experiences of loneliness across midlife and older age. Importantly, they also found that, men were more likely to be socially lonely, while women were more likely to experience emotional loneliness.

The inconsistent findings might be partly due to the reluctance of men to acknowledge feelings of loneliness openly. According to a study done by Aartsen et al. (2024), when asked indirectly rather than through direct measurements such as self-reports, men reported higher levels of loneliness. This discrepancy has been attributed to societal stigma, where loneliness is stigmatised more heavily in men than in women (Barreto et al., 2021; Lau & Gruen, 1992). Overall, inconsistencies between direct and indirect measurements underscore the need to consider methodological approaches when assessing gender differences in loneliness.

3.4. Technological Risk Factors

3.4.1. Digital Loneliness in a Hyperconnected World

The rise of digital technologies (e.g., social media, messaging, dating and friendship apps, artificial intelligence/AI chatbots) has profoundly reshaped how individuals interact, communicate, form and maintain social relationships leading to paradox in digital connectivity (Ahmed et al., 2024, Romano, 2024). The digital communication tools are particularly effective in facilitating and bridging social interaction, especially among digital nomads and immigrants (Miguel et al., 2024; Nowland et al., 2018). While they offer opportunities for people to connect across vast distances and at any time, they also increase emotional disconnection and reduce opportunities for high-quality interactions, further isolating individuals (Yavich et al., 2019; Shah et al., 2019; Masur, 2021; Miguel et al., 2024). They fail to replicate depth and quality face-to-face communication, which researchers define as "*digital loneliness*" (Miguel et al., 2024). This phenomenon stems from several factors, such as over-reliance on these digital platforms and a decline in meaningful in-person social bonds, which are essential for emotional intimacy (Masur, 2021; Shah et al., 2019).

Moreover, the proliferation of AI friends and romantic partners and virtual companions (e.g., Replika) reflect a growing trend towards artificial intimacy (Strohmann et al., 2023). However, this engagement may not be able to fulfil individuals' deeper social needs in forming meaningful connections and might deepen social isolation (Nowland et al., 2018). In summary, in a hyperconnected world, the challenge appears to be not the accessibility or availability of these digital communication tools but the cultivation of meaningful and deep connections.

3.4.2. Technology-Mediated Working and Studying

The COVID-19 pandemic has brought significant organisational changes into our lives at both macro and micro levels (Anand, 2024). One significant change is *working and studying remotely*, also called *technology-mediated working and studying* (Nguyen et al., 2024; Bareket-Bojmel et al., 2023). While this transition has enabled unprecedented levels of connectivity necessary during COVID-19 pandemic, it has also introduced paradoxical risks to social well-being in the long term (Becker et al., 2022). For instance, the State of Remote Work (Neat, 2024) reported that loneliness has emerged as the biggest struggle for individuals working remotely in the UK.

Recent research also suggests that digital connectivity reduces in-person environments, diminishing opportunities for spontaneous and casual interactions, which are essential for establishing and maintaining meaningful social connections (Van Der Lippe & Lippényi, 2020). While digital platforms enable online connection, they lack the emotional depth and meaningful *'connection'* (Kaufman & Vallade, 2022). Studies report that students engaging in online studying experience weaker social bonds and a reduced sense of belonging, and similarly, employees feel greater levels of loneliness (Kaufmann & Vallade, 2022; Afonso et al., 2022).

4. Prevalence of Loneliness

4.1. Global Trends in Loneliness

Despite the digitalised world and many emerging ways to connect with others, the prevalence of loneliness has increased across the world (Graham et al., 2024; Barreto et al., 2021). Hence, loneliness is a universally widespread phenomenon; however, its

prevalence and characteristics vary significantly across regions due to cultural, societal, and economic factors (Luhmann et al., 2023).

Surkalim et al. (2022) conducted a large systematic review and meta-analysis involving observational studies published between 2000 – 2019 across 113 countries to investigate the prevalence of loneliness measured with scales and single item instruments. They reported that the prevalence of loneliness in *the adolescent group* (12–17 years old) ranged from 9.2% in Southeast Asia to 14.4% in the Eastern Mediterranean region. For *young adults* (18-29 years), while pooled prevalence estimate was 5.3% (ranging from 4.4% to 6.4%); the prevalence was the highest in eastern Europe with 7.5% (5.9% to 9.4%) and the lowest in northern Europe with 2.9% (1.8% to 4.5%). For *middle-aged adults* (30 – 59 years), the pooled prevalence estimate was 6.9% (5.6% to 8.6%), while the prevalence was the lowest in northern Europe with 2.7% (2.4% to 3.0%) and highest in eastern Europe with 9.6% (7.7% to 12.0%) and central and western Asia with 9.8% (5.1% to 18.0%). For *older adults* (≥60 years), northern European countries had the lowest pooled prevalence with 5.2% (4.2% to 6.5%), followed by western Europe with 8.7% (7.3% to 10.5%), southern Europe with 15.7% (13.2% to 18.7%), and eastern European countries had the highest prevalence of loneliness with 21.3% (18.7% to 24.2). Overall, the study found that Northern Europe consistently reported the lowest rates of loneliness. At the same time, Eastern Europe had the highest loneliness rates across all adult age groups.

However, it is important to note that these findings also underscore major data gaps in low- and middle-income countries, where national prevalence data on loneliness, particularly by age group, remains scarce, limiting global comparisons and generalisability (Figure 10).

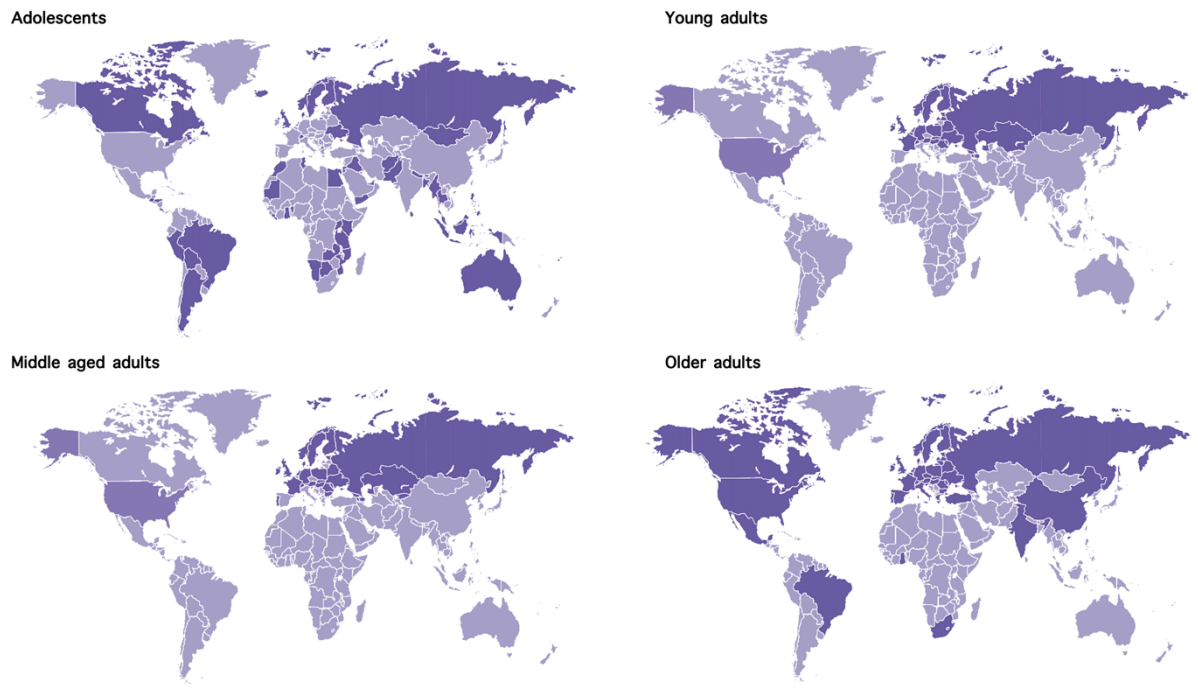


Figure 10. International Data Availability of National Prevalence of Loneliness by Age Group (Surkalim et al., 2022)

Note. Countries shaded in dark purple have national prevalence data available for the specific age group. Medium purple indicates countries where loneliness data is available only for adults aged 18 and over, without age-specific breakdowns. Light purple areas represent countries with no national prevalence data.

4.2. Demographic Variations in Loneliness

4.2.1. Age Related Loneliness

The findings on the trajectory of age across the lifespan are inconsistent. Some research suggested a U-shaped relationship between age and loneliness. Graham et al. (2024) reported results from nine longitudinal studies involving 128,118 individuals aged 13 to 103 from over 20 countries. They identified a consistent U-shaped curve pattern in which loneliness decreases from young adulthood to midlife but increases significantly in older adulthood, particularly after the age of 50 (Figure 11). Aligned with this, a sample study from Yang and Victor (2011) analysed loneliness across 25 European nations and reported that loneliness was highest among adolescents (5.9%) and older adults (16.9%), and middle-aged individuals reported the lowest rates.

In contrast, a recent meta-analysis including 75 longitudinal studies varying in durations, ranging from one to sixteen years, and using both direct and indirect measurement of loneliness, revealed that loneliness decreases from childhood to adolescence and stabilises thereafter (Mund et al., 2020). Similarly, Shovestul et al. (2020), using a US sample of 4,885 individuals aged 10 to 97 years who completed the three-item UCLA Loneliness Survey, reported that loneliness peaks at 19 years old and declines thereafter. Supporting this trend, an analysis of data from 46,054 participants aged 16–99 years across 237 countries in which loneliness was measured with UCLA-LSR found that loneliness decreases with age (Barreto et al., 2021).

These discrepancies in age-related trends might arise due to differences in study design, cultural contexts, and particularly measurement tools. For instance, Panayiotou et al. (2023) investigated the structural validity of the Revised UCLA Loneliness Scale (UCLA-LSR), which is the most widely used loneliness scale, across various age groups (18–99 years) in a UK population. They reported that the UCLA-LSR had inconsistent or poor fit across age groups for unidimensional, two-factor, and three-factor models. However, the 4-item (Russell et al., 1984), 8-item (Hays & DiMatteo, 1987), and 9-item UCLA Loneliness Scale (Hawkley et al., 2005), shorter forms of UCLA-LSR demonstrated better structural validity and full scalar measurement invariance, making it more robust across age groups. Overall, these contradictory findings highlight the complexity of age-related loneliness trajectories and emphasise the need for careful consideration of measurement tools and cultural contexts in future research to ensure more accurate and reliable conclusions.

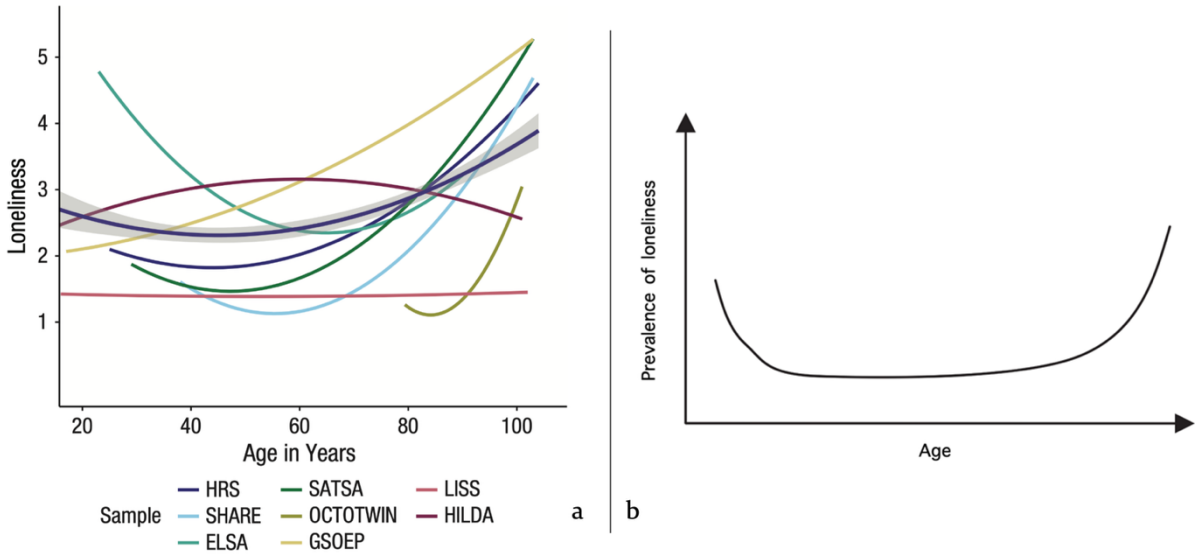


Figure 11. Age-Loneliness Trajectories

Note: (a) U-shaped curve with the black line showing the meta-analytic average, and coloured lines representing age trajectories from individual studies (Graham et al., 2024); (b) Non-linear relationship between age and the prevalence of loneliness (right; retrieved form Yang & Victor, 2011)

4.2.2. Gender Related Loneliness

Gender differences in loneliness have been widely investigated; however, the relationship is still inconclusive. Previous research has highlighted notable gender differences with contradictory findings on the prevalence and experience of loneliness. For instance, the data from the BBC Loneliness Experiment, including 46,054 participants aged 16–99 years, reported that the prevalence of loneliness was higher in men than in women of all ages (Barreto et al., 2021). Moreover, they also identified young males in individualistic cultures as particularly the most vulnerable to loneliness, whereas older females were more likely to report loneliness compared to older males (Barreto et al., 2021). Another meta-analysis with 638 studies involving 399,798 individuals (5-90 years old) across 45 countries also reported that gender differences were minimal, with males being slightly lonelier than females on average (effect size g=0.07; Maes et al., 2019).

In contrast, in a 15-year longitudinal study comprising 2,315 individuals aged 40 to 80 years old, Nicolaisen and Thorsen (2024) found that women consistently reported higher levels of loneliness than men across all age groups and time points in their longitudinal study. Moreover, even after adjusting for health, partnership and sociodemographic factors, the gap was largest in older age. Although there is a difference, their findings supported the broader consensus that young males represent the loneliest demographic, whereas older men are consistently the least lonely. Another population-based cohort study of the older population in Germany with sample of 2,171 older women and men and noted that loneliness was more prevalent in women (Boehlen et al., 2023). Similarly, in a longitudinal study with 13,222 participants aged 65 or older, Torres et al. (2024) found that women reported higher levels of loneliness compared to men.

Overall, these discrepancies among studies might indicate that the relationship between gender and loneliness is influenced by factors such as age, cultural context, and measurement tools, underscoring the complex nature of loneliness.

5. Consequences of Loneliness

5.1. Physical Health Consequences

Loneliness impacts physical health in a variety of ways, particularly with a strong correlation between loneliness and mortality and cardiovascular health (Leigh-Hunt et al., 2017). Studies have demonstrated that loneliness led to reduced protective hormones, which consequently have negative impacts on cardiovascular health with increased risks for blood pressure, coronary heart disease, stroke blood pressure and the repair of blood vessel walls (Lim et al., 2023; Leigh-Hunt et al., 2017; Quadt et al., 2020).

According to a longitudinal study, lonely individuals have a 29% higher risk of coronary heart disease and a 32% increased risk of stroke (Valtorta et al., 2016). Loneliness has also been linked to the immune system downregulation and neuroendocrine dysregulation, causing insufficient or poor quality of sleep (Mushtaq et al., 2014; Cacioppo et al., 2002); smoking and obesity (Lasgaard et al., 2025). Furthermore, longitudinal studies revealed that loneliness contributes to the development and exacerbation of metabolic conditions such as diabetes and obesity (Cho et al., 2025; Rokach & Patel, 2024).

Additionally, loneliness increases the susceptibility to chronic illnesses, including respiratory diseases, gastrointestinal conditions, and cancer, with evidence suggesting that loneliness exacerbates the progression of these diseases through persistent systemic inflammation and oxidative stress (Meng et al., 2024; Mushtaq et al., 2014). Another critical area is the interaction between loneliness and neurophysiological processes. Literature highlights that loneliness-related stress alters the brain and body communication by impairing allosteric regulation and contributing to neurodegenerative diseases such as dementia (Park et al., 2020; Maes & Vanhalst, 2024; Quadt et al., 2020). A large-scale meta-analysis of 148 studies involving more than 300,000 participants reported concerning results suggesting that loneliness significantly increased the mortality risk by 26% (Holt-Lunstad, 2015). This effect remained significant even after controlling for other health-related variables, indicating that loneliness is a risk factor for premature death independently. Researchers also reported the impact of loneliness at the cellular levels which suggests that loneliness might be accelerating biological ageing (Hawkley et al., 2009). Overall, these findings suggest that

loneliness is not only an emotional experience but a significant public health problem with physical health consequences.

5.2. Mental Health Consequences

There are accumulative results from longitudinal research suggesting that loneliness predicts increased morbidity (Schutter et al., 2022; Rico-Uribe et al., 2018; Yanguas et al., 2018). One of the most consistently documented consequences of loneliness is its strong association with *depression* (Mann et al., 2017). Lonely people often report increased feelings of worthlessness, hopelessness, and reduced self-esteem (Çutuk, 2021; Harrison et al., 2022). Moreover, *anxiety*, which is characterized by hypervigilance and fear of social judgment, is another adverse consequence of loneliness (Lim et al., 2016; Hutten et al., 2021a; Mushtaq et al., 2014). Along with emotional challenges, loneliness also affects cognitive functioning, resulting in impaired executive function, self-regulation and emotion regulation, poor sleep memory, predicting cognitive decline, and increased risk of dementia (Elovainio et al., 2022; Junttila et al., 2015; Rokach & Patel, 2024).

Studies suggest that in severe cases, loneliness and social isolation contribute to development of personality disorders and psychosis due to paranoia and maladaptive beliefs stem from mechanisms such as chronic stress and reduced mental stimulation (Pourriyahi et al., 2021; Mushtaq et al., 2014; Pitman et al., 2018). Moreover, loneliness is also a significant predictor of suicidal thoughts and behaviour, particularly among young people and marginalised groups, where social stigma exacerbates feelings of social disconnection (Pitman et al., 2018). Studies reported that people with strong support networks are better equipped to effectively cope with the adverse impacts of

loneliness, emphasising the importance of strong social connections to mitigate the psychological burden of loneliness (Hutten et al., 2021a; Mushtaq et al., 2014). In conclusion, loneliness stands a major public health problem with broad implications for mental and social well-being.

5.3. Social and Societal Consequences

Loneliness is not just an individual emotional experience, it extends far beyond physical and mental health problems, carrying significant social consequences, such as interpersonal functioning, community engagement, and broader public health systems.

At an *interpersonal level*, loneliness causes social withdrawal, gradual erosion of social skills and interpersonal mistrust (Weigert, 1960; Rotenberg, 1994). These interpersonal dynamics potentially weaken broader social cohesion (Holt-Lunstad et al., 2021). Community networks become increasingly fragmented which diminish collective social resilience and mutual support networks as lonely individuals socially withdraw (Barreto et al., 2024). At a *community level*, loneliness undermines social capital and civic engagement (Juntilla et al., 2015). Individuals who feel socially excluded or devalued are less likely to engage in communal activities, volunteerism, or democratic processes (von Humboldt et al., 2024; Crawford et al., 2023). This reduction of social engagement diminishes the fabric of collective social life, potentially weakening social cohesion and trust (Lim et al., 2024). At a *public health* level, it is crucial to understand the economic burden loneliness as it has been associated with increased reliance on social services and healthcare systems (Mihalopoulos et al., 2020). For instance, individuals experiencing chronic loneliness are more likely to seek medical consultations for both psychological distresses, and physical health problems

exacerbated by loneliness (Leigh-Hunt et al., 2017). Moreover, according to New Economics Foundation and The Coop (2017), UK employers estimate that loneliness costs £2.5 billion per year through reduced productivity because of lower wellbeing and sickness absence caused by loneliness.

6. Integrative Chapter Summary

This introduction chapter provides a comprehensive multidisciplinary foundation to understand loneliness as a complex, multilayered and dynamic phenomenon. The chapter conceptualises loneliness as a multidimensional experience shaped by neurobiological, cognitive, psychological, cultural and technological factors, unfolding across time and context.

The chapter advances a taxonomy of loneliness that integrates both temporal and dimensional perspectives. Temporally, loneliness may be situational (transient), arising from life transitions such as loss, migration, or role change; or chronic, characterised by experiencing difficulties in forming or maintaining meaningful relationships. Dimensionally, loneliness is conceptualised across four interrelated domains: emotional (intimate), social (relational), collective and existential loneliness in which they operate orthogonally to time, such that any dimension may co-occur with situational or chronic loneliness. This framework moves beyond binary classifications and allows for a nuanced understanding of how loneliness manifests differently across individuals and contexts.

Theoretical frameworks explain loneliness through various disciplines. Evolutionary theory frames loneliness as an adaptive signal designed to motive social reconnection and enhance survival, however, paradoxically, reinforces hypervigilance to social cues

and withdrawal, potentially leading to cognitive biases. Neuroscientific research highlights structural and functional brain alterations, particularly in the amygdala, prefrontal cortex, insula, and ventral striatum that disrupt emotion regulation, social processing, and reward sensitivity, perpetuating negative cognitive biases. Cognitive-behavioural models, which hold a central role in this PhD thesis, underscore how maladaptive thoughts and behaviours perpetuate loneliness, with attention, interpretation, and approach-avoidance biases playing pivotal roles. Social theories illustrate how loneliness spreads through networks and become contagious, and how perceived social threats drive inflammatory responses and withdrawal.

A wide range of risk factors are integrated across levels of analysis. Biological vulnerabilities (including genetic, neuroendocrine, and inflammatory processes), psychological factors (attachment styles, mental health conditions, personality traits), sociocultural contexts (individualism–collectivism, urbanisation, migration), demographic variables (age and gender), and technological advancements (digital communication, remote work and study, artificial companionship) all interact to shape vulnerability to loneliness. Importantly, no single factor is sufficient; loneliness emerges from intersecting risks operating across the lifespan.

The prevalence of loneliness varies globally, with age-related patterns showing either a U-shaped trajectory or a linear decline. Meanwhile, gender differences remain inconclusive, though some studies suggest men may experience loneliness more intensely due to societal stigma.

Finally, the chapter documents the far-reaching consequences of loneliness, extending well beyond emotional distress. Loneliness is associated with increased morbidity and mortality, cardiovascular and immune dysfunction, cognitive decline,

mental health disorders, suicidality, and substantial societal and economic costs. These outcomes underscore loneliness as a major public health challenge, not merely a private emotional experience.

In sum, this chapter establishes loneliness as a multilevel, self-reinforcing, and context-sensitive phenomenon. By integrating evolutionary theory, neuroscience, cognitive-behavioural psychology, social theories, and epidemiology, it provides a unifying framework that explains how loneliness originates, persists, and impacts individuals and societies. This integrative foundation sets the stage for the thesis' central focus on cognitive biases as modifiable mechanisms, offering a theoretically grounded pathway for advancing both scientific understanding and intervention development in loneliness research.

CHAPTER 2

Study 1

A Scoping Review of Experimental Studies on Cognitive Biases in Loneliness

"We do not see the world as it is, we see it as we are."

Anaïs Nin

Abstract[1]

According to evolutionary theory, while loneliness motivates people to socially reconnect with others, paradoxically, it also contributes to hypervigilance to negative cues and cognitive biases, potentially as an adaptive self-protection mechanism. The current scoping review aimed to elucidate the nature of these biases by synthesising experimental studies examining three key biases: *attention*, *interpretation*, and *approach-avoidance* biases, in the light of "Social Information Processing Theory", to identify patterns and methodological gaps. Hence, a literature search was conducted systematically across PubMed, PsycINFO, Scopus, and Web of Science, and 28 experimental studies were identified that investigated cognitive biases in loneliness using different experimental techniques. Evidence from children and adolescents was limited and therefore remains inconclusive. Across studies assessing attention bias, the examination yielded mixed results. While some findings suggested that loneliness is associated with attention bias to negative cues, others found no bias. However, neuroimaging studies consistently showed loneliness to be associated with increased neural responses to negative cues, suggesting early-stage hypervigilance despite behavioural variability. In contrast, findings on interpretation biases were more consistent, where lonely adults tend to interpret neutral or ambiguous social scenarios and messages more negatively. Despite of limited findings, one of the most valuable insights was about approach-avoidance bias, where situational loneliness increased approach motivation, while chronic loneliness reinforced avoidance behaviour, reflecting the loneliness paradox between motivation to reconnect and fear of rejection. Therefore, we argue that approach–avoidance biases offer a particularly compelling framework for understanding loneliness. We also highlight the need for more experimental research involving children and adolescents, as well as improved methodological focus on distinguishing between situational and chronic forms of loneliness.

[1] *This paper has been submitted to a peer-reviewed journal and is currently under review.*

1. Introduction

Human beings thrive on meaningful connections; hence loneliness is an inherent part of human existence, experienced by all at some point in their lives (Spithoven et al., 2017; Cacioppo & Hawkley, 2009). Loneliness emerges when there is a subjective discrepancy between desired and perceived interpersonal relationships in terms of both quality and quantity (Peplau & Perlman, 1982). This experience may be situational (such as losing a loved one or a job, moving to a new place, separation, or retirement) or chronic (prolonged state arising from a person's long-standing difficulty in forming or maintaining meaningful social connections), occur frequently or rarely, and vary in intensity (Shiovitz-Ezra & Ayalon, 2010). While transient episodes of loneliness (i.e., situational loneliness) can motivate people to socially reconnect, chronic loneliness can lead to a wide range of adverse psychological and physical health outcomes, including increased morbidity and mortality (Lim et al., 2023; Schutter et al., 2022). Loneliness, whether situational or chronic, is influenced by a complex interplay of neurobiological, psychological, evolutionary, social, and environmental factors, and it has been a focus of various theoretical models seeking to explain its origins, maintenance and how it might affect the cognitive processes of individuals.

1.1. Evolutionary Theory of Loneliness

One of the most influential models describing loneliness in the context of modern life is the “Evolutionary Theory of Loneliness” which was proposed by Cacioppo (2006) and later expanded by Cacioppo and Hawkley (2009) to demonstrate the impact of loneliness on human cognition. This model proposes that loneliness is a hereditary trait,

like hunger, thirst and pain, which evolved for an organism to change its behaviour for survival. In our evolutionary past, the feeling of loneliness protected us from the danger of remaining isolated and served as an adaptive mechanism to improve our chances of survival as a species (Cacioppo & Hawkley, 2009). Thus, the awareness of loneliness evolved to serve as a signal for frayed and broken connections and to drive people to repair and maintain those connections (Baumeister & Leary, 2017). However, this adaptive mechanism which increases hypervigilance to social cues can paradoxically lead to a greater fear of connecting with others and become a maladaptive mechanism (Maes et al., 2019; Cacioppo et al., 2014). Specifically, studies show that loneliness promotes a cognitive bias towards perceiving social threats, through attention, confirmatory and memory biases (Cacioppo et al., 2014). These biases lead to negative expectations, which shape individuals' behaviour in social situations with more negative displays, such as withdrawing or avoiding social interactions and this, in turn, reinforces the behavioural confirmation process (Spithoven et al., 2017). Eventually, this creates a self-reinforcing loop which ultimately perpetuates the feeling of loneliness. Hence, lonely people may view themselves as passive victims in their social world even though they are the active contributors through self-protective and bias-driven interactions with others (Cacioppo & Hawkley, 2009; London et al., 2007).

1.2. Cognitive Biases and Social Information Processing in Loneliness

Cognitive biases are systematic distortions in thinking that affect how individuals interpret and respond to social and emotional cues, often reinforcing negative social expectations (Korteling et al., 2018; Kahneman & Tversky, 1984). The

hypervigilance to these negatively perceived cues was explained by a prominent loneliness researcher, Weiss (1973, *p. 21*), as follows: *"The individual is forever appraising others for their potential as providers of the needed relationships, and forever appraising situations in terms of their potential for making the needed relationships available. However, loneliness produces an oversensitivity to minimal cues and a tendency to misinterpret or to exaggerate the hostile or affectionate intent of others."*. Cacioppo's evolutionary model of loneliness supports this perspective, suggesting that hypervigilance leads lonely individuals to excessively monitor their social environment for signs of rejection or hostility (Cacioppo et al., 2009). Building upon this model, Qualter et al. (2015) examined loneliness through the Reaffiliation Motive (RAM) model, explaining how perceived social isolation triggers a cycle of cognitive and behavioural responses that can either perpetuate loneliness or facilitate reconnection. They identified hypervigilance as a critical stage in which chronic loneliness reinforces negative cognitive biases, increasing social withdrawal and emotional distress, and how interventions targeting this stage could help break the cycle and promote social re-engagement. Building on this cognitive and affective dysregulation, recent studies started focusing on brain areas involved in social cognition. Several research reported the medial prefrontal cortex (mPFC) and temporo-parietal junction as key regions involved in self-reflection, understanding others' thoughts and emotions, and navigating complex social situations (Bengtsson et al., 2011; Lieberz et al., 2021; Morese & Palermo, 2022). Moreover, Morese and Palermo (2022) argue in their opinion piece that the repeated effects of the loneliness loop may contribute to social deprivation, frailty and neurodegeneration over time.

Correspondingly, Spithoven et al. (2017) suggested that this maladaptive cognitive processing can be understood through *the Social Information Processing* (SIP; Crick, 1995), which was originally designed to explain social cognitions of socially adjusted or maladjusted children. According to this model, social cognition is shaped by a series of cognitive steps: (1) attention and decoding of the cues; (2) interpretation of the cues; (3) goal-driven behavioural response selection; and (4) behavioural enactment. Spithoven et al. (2017) highlighted that lonely individuals deploy the same social information processing across all these stages, particularly in interpreting social cues negatively, expecting rejection, and engaging in self-defeating behaviours compared to non-lonely individuals. Therefore, the role of the SIP model is crucial to understand loneliness, as processing social information is necessary for effective communication, social interaction, and maintaining interpersonal relationships (Taylor & Crocker, 2022; Adolphs, 2003).

By integrating Cacioppo's (2019) evolutionary model on loneliness, Qualter et al.'s (2015) RAM model and Morese et al.'s (2022) arguments on the neural underpinnings of loneliness with the SIP model's cognitive framework (Crick, 1995), it becomes evident that loneliness is not only an emotional state but includes cognitive and neurobiological processes that reinforce social withdrawal and distress with long-term psychological and physiological consequences.

However, despite growing interest in this topic, there is still no comprehensive synthesis of experimental studies exploring the impact of cognitive biases on loneliness through "Social Information Processing Theory".

In order to explore these cognitive biases in detail, we adapted the evolutionary model from Cacioppo and Hawkley (2009), which originally included attentional, confirmatory, and memory biases as cognitive mechanisms reinforcing the cycle of loneliness. This model was refined in this review to focus specifically on *attention*, *interpretation*, and *approach-avoidance* biases in the light of cognitive steps in Crick's SIP framework to demonstrate their relevance in cognitive and behavioural mechanisms in the vicious cycle of loneliness in the light of cognitive steps in SIP framework (Figure 12).

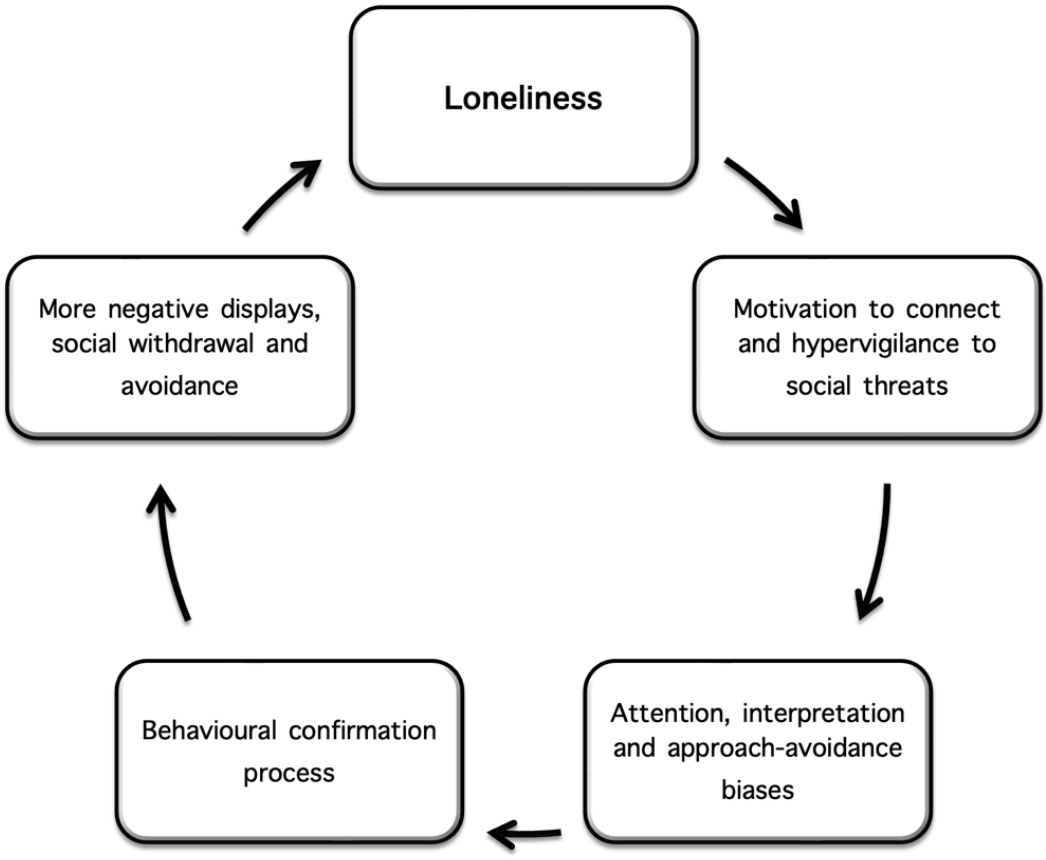


Figure 12. A Self-reinforcing Cycle of Loneliness: Cognitive and Behavioural Mechanisms (adapted from Cacioppo & Hawkley, 2009, with modifications)

1.2.1. Attention Bias

Attention bias typically refers to the selective allocation of attention to certain types of stimuli (Crump et al., 2018). Edwards et al. (2021) suggested that attentional responses are shaped through the integration of socially meaningful signals, such as facial emotions. Attention bias is commonly studied by measuring reaction times using computerised tasks, such as the Emotional Stroop Task or Visual Probe Task (Amaro-Diaz et al., 2022; Rooney et al., 2024); by examining gaze patterns and eye movements using eye tracking, and to assess brain activity in response to social and emotional stimuli using neuroimaging techniques, such as fMRI. In the context of loneliness, this often manifests as a tendency to focus more quickly or longer fixations on negative social information (Henricks et al., 2022). The over-focus on negative cues in lonely individuals could manifest itself as perceived rejection or hostility, while potentially disregarding positive or even neutral social and emotional information (Cacioppo et al., 2006; Grennan et al., 2021; Du et al., 2022). This selective attention has been linked to neurobiological mechanisms, including hyperactivity in the amygdala, which is involved in the processing emotional stimuli, and dysfunction in the prefrontal cortex, which plays a role in cognitive control (Morr et al., 2022a; Lam et al., 2021). Attention bias is often intertwined with other biases, such as interpretation bias.

1.2.2. Interpretation Bias

While attention bias determines what people focus on, *interpretation bias* involves the cognitive processes of making sense of social and emotional information (Chen et al., 2020). In the context of loneliness, this often includes a tendency to interpret ambiguous and/or neutral social cues negatively (Patel et al., 2024; Lau et al., 2021).

Interpretation bias is typically measured by assessing individuals' ability to identify and interpret valence of emotional, neutral, or ambiguous social cues (decoding accuracy; Klein et al., 2019; Lange et al., 2010). According to previous studies, lonely individuals are prone to misinterpret ambiguous cues as being indicative of rejection or social threat, which can hinder the formation and maintenance of social connections (Nombro et al., 2022). Skoko et al. (2024) conceptualised a mediation model showing that negative interpretation bias was directly associated with increased level of loneliness. They also found that social avoidance behaviours, such as discomfort or fear of rejection or negative evaluation, mediated this relationship. Thus, interpretation bias plays a relevant role in the social engagement of lonely individuals.

1.2.3. Approach-Avoidance Bias

Approach-avoidance bias (AAB) is characterised by altered automatic behaviours towards emotional and social stimuli (Loijen et al., 2020; Wiers et al., 2010). Approach-avoidance motivation was first theorised and operationalised by Pavlov (1927), who described it as a physiological system based on the orientation of an organism toward a positive stimulus and away from a negative stimulus. Building upon this theory, Gable (2005) highlighted that interpersonal relationships inherently present potential threats as well as potential incentives and proposed "A Model of Approach and Avoidance Explaining Interpersonal Social Motivation" (Gable & Gosnell, 2013, *p.270;* Figure 13). According to this model, each individual's sensitivity to social reward and threat, along with one's social environment influence goals through two parallel pathways: approach motives (e.g., "to make friends", "to spend more quality time with my spouse") and avoidance motives (e.g., "to not be lonely", "to not argue with my spouse"). These

motivational tendencies ultimately shape global relationship outcomes, such as satisfaction or loneliness (Gable & Gosnell, 2013). In fact, the association between social avoidance-approach behaviours and loneliness has been investigated in cross-sectional longitudinal studies through self-report surveys which reported that as loneliness increases, social avoidance tends to increase as well (Maitland, 2020; Layden et al., 2018; Johnson et al., 2001; Nurmi et al., 1997; Crick & Ladd, 1993). Therefore, we argue that is important to take the approach-avoidance bias into account when researching the paradoxical behaviour of lonely individuals, characterised by a simultaneous desire for social connection and social avoidance caused by hypervigilance of social threat (Cacioppo & Hawkley, 2009).

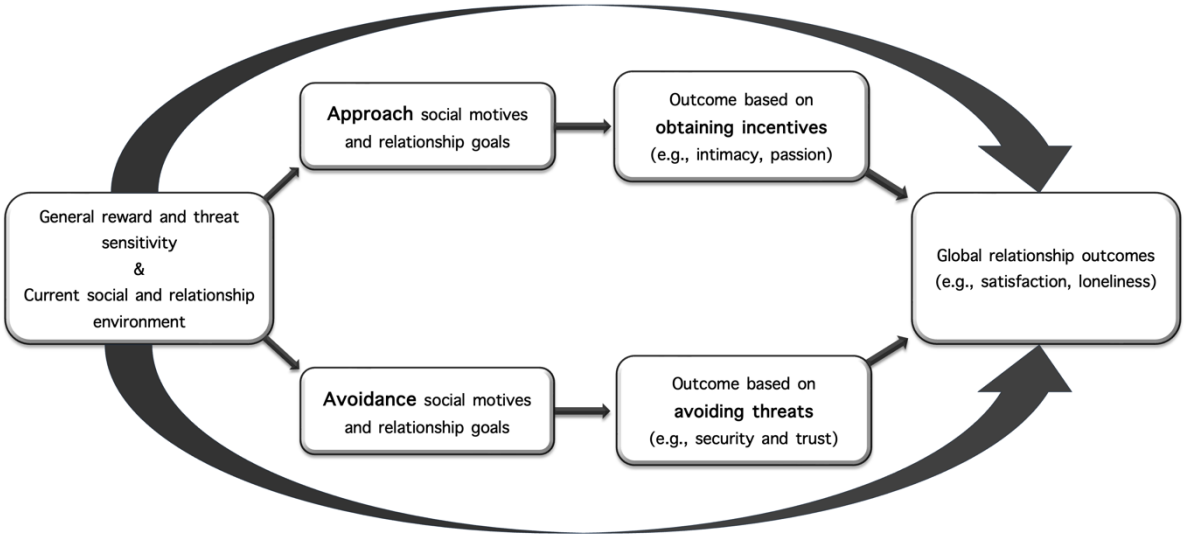


Figure 13. The Model of Approach–Avoidance Interpersonal Motivation (retrieved from Gable & Gosnell, 2013)

Collectively, these cognitive biases not only shape the emotional and social perceptions of individuals but also influence long-term social connections. While various theoretical models highlight how attention, interpretation, and approach-

avoidance biases contribute to the self-reinforcing cycle of loneliness, empirical investigations remain scattered across diverse methodologies. In the current review, we focused on the contribution of experimental studies; tasks measuring reaction times, eye-movements, brain activation, decoding accuracy and interpersonal distance with following aims to:

i. Systematically map the landscape of experimental studies on cognitive biases in loneliness in terms of social information processing.
ii. Identify key methodological approaches.
iii. Synthesise the empirical evidence related to attention, interpretation, and approach-avoidance biases.
iv. Identify research gaps (e.g., theoretical, methodological, empirical, knowledge, evidence, population, and conceptual) to inform future studies.

RQ: What is known about *attention, interpretation* and *approach-avoidance* biases in loneliness in terms of social information processing based on experimental studies?

2. Methods

2.1. Study Design

This review follows the framework of Arksey and O'Malley (2005) which includes five steps: (1) identifying the research questions; (2) identifying relevant information; (3) study selection; (4) charting the data; (5) collating, summarising and reporting the results. The review protocol has been registered on the Open Science Framework (https://osf.io/uckzy/).

2.2. Inclusion Criteria

Studies were included based on the following inclusion criteria:

i. Experimental studies (e.g., computerised, eye tracking, EEG, ECG, MRI, fMRI).

ii. Measurement of loneliness.

iii. Experimental paradigms including visual, auditory and/or linguistic stimuli (e.g. static images, video clips, morphed videos, voices, sounds, words, scenario vignettes) that either measure reaction time, response time, accuracy, gaze, fixation, neural activation, ERP components, or PNS activity.

iv. Examination of attention, interpretation, or approach-avoidance biases.

v. Studies investigating loneliness without comorbid conditions as primary variables.

vi. Published in peer-reviewed journals in English.

2.3. Literature Search Strategy

A comprehensive systematic search was conducted across databases including PubMed, PsycINFO, Scopus, and Web of Science, up to August 2025. The search was performed using terms related to loneliness, cognitive biases, experimental studies and experimental paradigms (Table 2). We also employed manual search on other online platforms (e.g., ResearchGate, Google search) for grey literature. References of included studies were also checked for relevant studies.

Table 2. Strategy Employed for Relevant Articles

Key Concepts	**Related Keywords and Terms**
Loneliness	"loneliness" OR "social isolation" OR "perceived social isolation" OR "state loneliness" OR "chronic loneliness" OR "lonely" OR "subjective social isolation" OR "situational loneliness" OR "transient loneliness"
Cognitive biases	"cognitive bias" OR "attention bias" OR "attention" OR "interpretation bias" OR "interpretation" OR "approach avoidance bias" OR "avoidance bias" OR "approach bias" OR "social monitoring" OR "hypervigilance" OR "attribution bias" OR "negativity bias"
Experimental studies	"experimental" OR "computer-based" OR "computerised" OR "eye-tracking" OR "EEG" OR "fMRI" OR "MRI" OR "ERP" OR "Drift Diffusion Model" OR "neural correlates" OR "brain activity"
Experimental paradigm	"visual attention" OR "auditory Stroop task" OR "social Stroop task" OR "dot probe task" OR "facial emotion processing" OR "facial emotion recognition" OR "visual search task" OR "emotional Stroop task" OR "flanker task" OR "Go/No-Go task" OR "covert attention task" OR "emotion recognition task" OR "visual oddball task"

2.4. Data Synthesis and Analysis

This review adhered to the PRISMA-ScR guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews; Tricco et al., 2018; Figure 14). Initial duplicates were removed using Mendeley reference management software. Prior to main data extraction, a pilot data extraction of 12 sources was carried out to trial the data charting framework. Titles and abstracts of the identified articles were screened based on eligibility criteria, followed by full-text assessments using web-based software Rayyan (Rayyan, 2020; www.rayyan.ai). Data were extracted using a narrative and thematic approach to capture study characteristics (e.g., authors, year, and country), measures, materials, experimental techniques, experimental paradigms, and key findings. Results were synthesized descriptively and thematically to highlight

common themes, methodological patterns and gaps in the literature. The search was initially conducted in December 2024 and updated in August 2025.

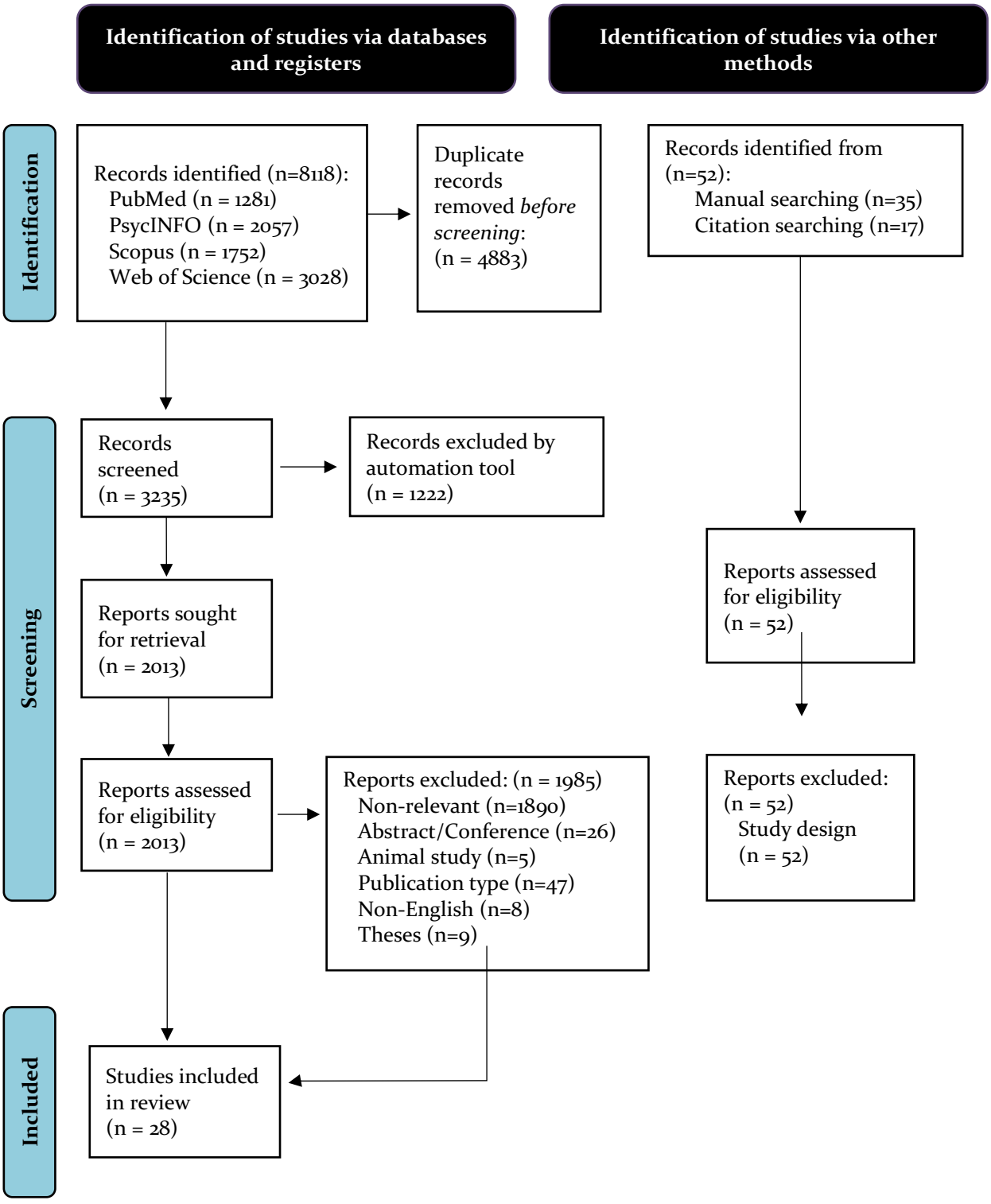


Figure 14. PRISMA Flowchart Showing Study Identification, Screening and Selection Process for the Included Articles

3. Results

3.1. Characteristics of the Studies

A total of 28 studies met the inclusion criteria, spanning diverse populations and experimental methods published between 2001 and 2024 (Figure 15). Among them, 19 focused on attention bias, 16 examined interpretation biases (9 studies included both attention and interpretation biases) and 2 investigated approach-avoidance bias. Sample sizes ranged from small cohorts, such as 19 participants in Cacioppo et al. (2015), to larger groups, including 591 participants in Grocott et al. (2024). Studies targeted diverse age groups, from children (e.g., 8–13 years old; Qualter et al., 2013) to older adults (e.g., 55–90 years old; Ypsilanti et al., 2020) across multiple countries, including Belgium, Canada, China, Israel, Netherlands, Poland, South Korea, UK, USA, and Japan. The studies employed diverse psychometric measures but mostly used the UCLA for loneliness, CES-D for depression, and GAD-7 for anxiety. The included experimental materials were such as static images, video clips, morphed videos, words, vocal stimuli, IAPS database pictures and scenario vignettes. Methodologies included predominantly computerised tasks (e.g., facial emotion processing task), sometimes in combination with EEG, ECG, MRI, fMRI, eye-tracking and traditional paper-based methods (Figure 16).

Table 3 outlines the distribution of experimental studies examining cognitive biases associated with loneliness, and Table 4 summarises the characteristics and key findings of the included experimental studies in this review.

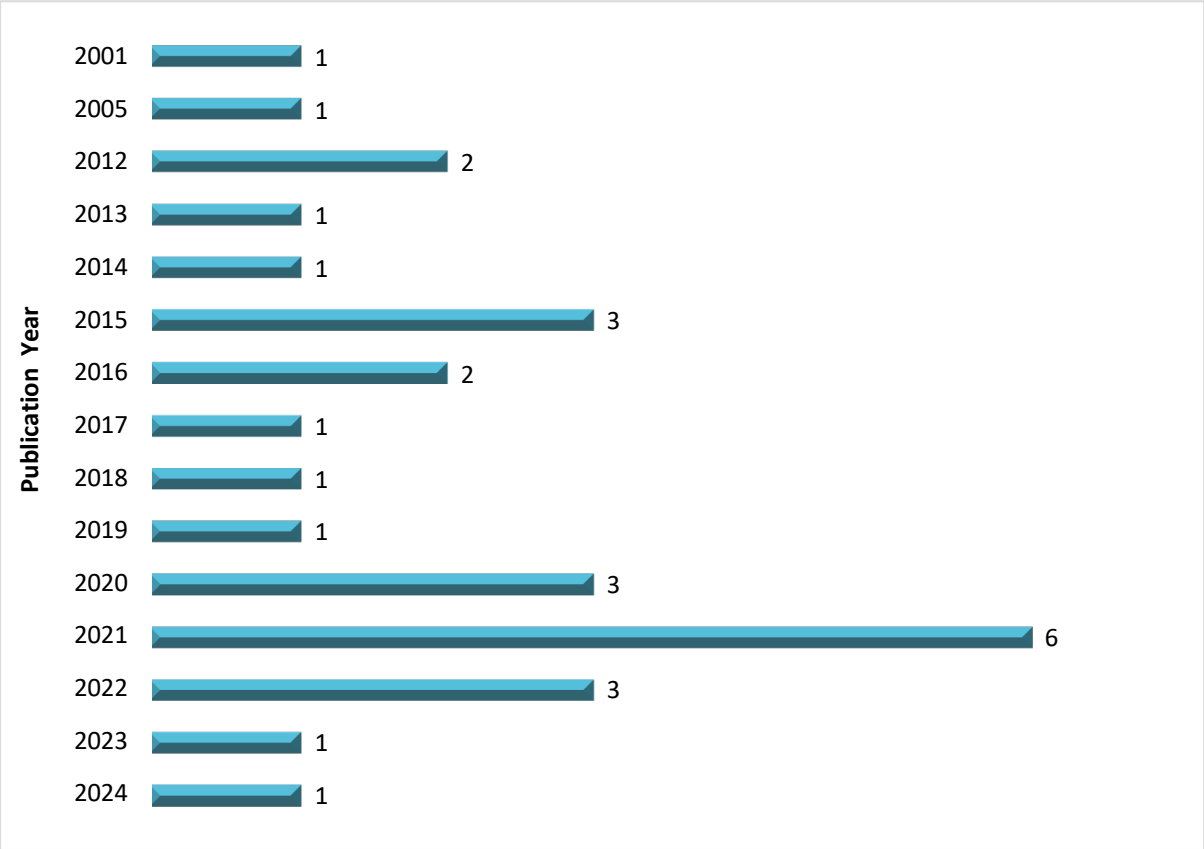


Figure 15. Distribution of Published Studies in This Review by Publication Year (N = 28)

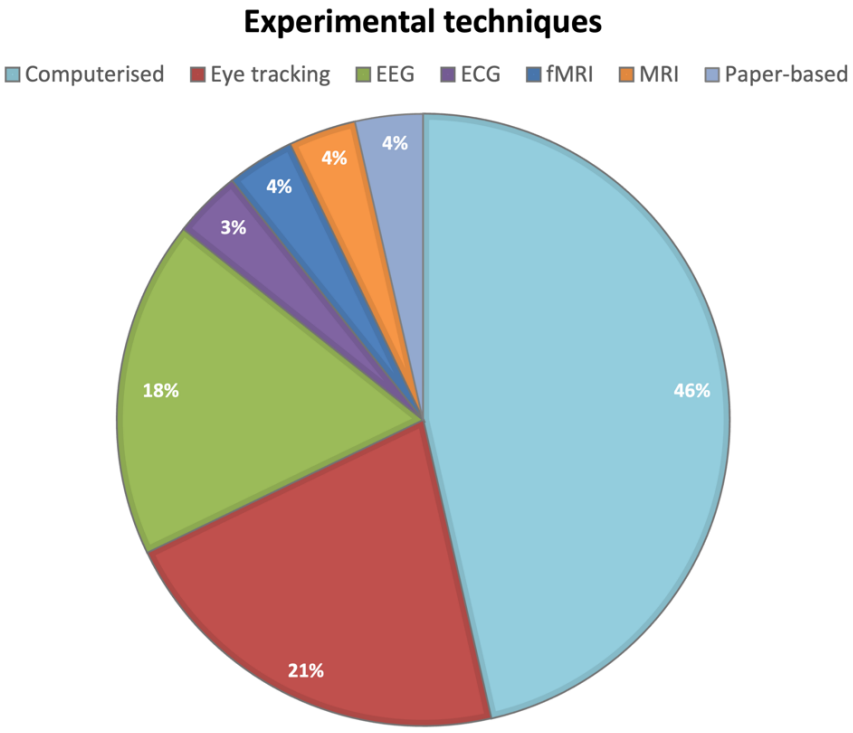


Figure 16. Distribution of Research Methodologies in the Included Studies (N = 28)

Table 3. Distribution of Experimental Studies Included by Cognitive Biases in Loneliness

Study (Author and year)	Attention	Interpretation	Approach-Avoidance
Edwards et al. (2001)		x	
Gardner et al. (2005)	x	x	
Cacioppo et al. (2009)	x	x	
Kanai et al. (2012)	x	x	
Zysberg (2012)		x	
Qualter et al. (2013)	x		
Bangee et al. (2014)	x		
Cacioppo et al. (2015)	x	x	
Lodder et al. (2015)	x		
Cacioppo et al. (2016)	x	x	
Lodder et al. (2016)	x	x	
Vanhalst et al. (2017)	x	x	
Bangee & Qualter (2018)	x		
Shin & Kim (2019)	x		
Morningstar et al. (2020)		x	
Saito et al. (2020)	x		
Ypsilanti et al. (2020)	x		
Cheeta et al. (2021)	x	x	
Grennan et al. (2021)	x		
Lau et al. (2021)		x	
Okruszek et al. (2021)		x	
Saporta et al. (2021)			x
Du et al. (2022)	x		
Nombro et al. (2022)		x	
Smith et al. (2022)	x	x	
Smith & Pollak et al. (2022)			x
Maka et al. (2023)	x		
Grocott et al. (2024)		x	

Table 4. Summary of Characteristics and Key Findings of Experimental Studies in Cognitive Biases in Loneliness

	Author Year Country	Type of cognitive bias	N Age	Measures Materials	Experimental technique	Experimental paradigm	Key findings
1	Edwards et al. 2001 USA	Interpretation	173 18 - 26	R-UCLA VAS Scenario Vignettes	Paper-based	Participants completed two ambiguous scenarios and rated the degree of negative and positive interpretation using Likert-type items.	Lonely adults interpreted ambiguous scenarios significantly more negatively than non-lonely adults.
2	Gardner et al. 2005 USA	Attention Interpretation	Study 2 74 N/A	R-UCLA PANAS Words (positive vs negative) Static Images (anger, fear, happy, sad)	Computerised	University students completed the Vocal Emotional Stroop task identifying word valence while ignoring vocal tone. Participants then completed DANVA-2 with low-intensity emotional faces lasting 1-sec and identified the emotion.	Participants with fewer friends showed increased attention to vocal tone, regardless of whether the tone was positive or negative, as shown by a greater response time difference between congruent and incongruent trials. They also had higher accuracy in identifying facial expressions with low emotional intensity.
3	Cacioppo et al. 2009 USA	Attention Interpretation	23 N/A	UCLA-3 IAPS Images (pleasant social, pleasant non-social, unpleasant social, unpleasant non-social)	fMRI	Female university students viewed 160 images presented for 6 seconds, with jittered intertrial intervals to allow for deconvolution of the hemodynamic response. Then, they categorised the valence of each image by pressing one of three buttons (neutral, negative, positive). Meanwhile, functional brain activity was recorded.	Lonely participants showed reduced activation in the ventral striatum, dorsal mPFC, anterior insula, and fusiform gyrus when viewing pleasant social stimuli compared to pleasant non-social stimuli. They also displayed increased activation in the bilateral visual cortex in response to unpleasant social stimuli compared to unpleasant non-social stimuli, suggesting a heightened attentional focus on social negative cues. Moreover, lonely individuals did not show difference between social and non-social image sin valence rating.
4	Kanai et al. 2012 UK	Attention Interpretation	Study 2 22 19 - 30	UCLA-3 STAI Static Images (happy, angry, sad, fear)	MRI	Participants completed four tasks assessing social perception: abnormal gaze detection by identifying deviations in eye gaze direction; emotion discrimination by identifying facial emotion; identity discrimination by recognizing facial identity differences; and film emotion recognition by identifying emotions in video clips.	Lonely adults showed reduced accuracy in eye-gaze perception but no significant differences in general emotion or face-identity recognition. Neuroimaging findings revealed reduced gray-matter volume in the left posterior superior temporal sulcus (pSTS), linking structural brain differences to deficits in gaze perception in loneliness.

	Author Year Country	Type of cognitive bias	N Age	Measures Material	Experimental technique	Experimental paradigm	Key findings
5	Zysberg 2012 Israel	Interpretation	Study 2 134 20 - 29	UCLA-R Static Images Video clips	Computerised	Participants were presented with *Audio-Visual Test of Emotional Intelligence (AVEI*) to identify the emotions in 27 images and short video clips.	Loneliness was associated with lower emotional intelligence scores, indicating reduced accuracy in recognising others' emotions.
6	Qualter et al. 2013 UK	Attention	Study 3 140 8 – 12	LACA CDI Video Clips (positive vs negative social interactions)	Eye tracking	Participants watched eight 20-sec video clips of social interactions, containing both socially threatening (e.g., rejection) and non-threatening (e.g., positive) behaviours.	Lonely children showed attention bias towards social threats by fixating longer on threatening stimuli and taking up to 20 seconds to disengage, compared to 5 seconds for non-lonely peers. This bias was most pronounced in the upper quartile of loneliness scores.
7	Bangee et al. 2014 UK	Attention	85 17-19	UCLA-3 Video Clips (positive vs negative social interactions)	Eye tracking	Eight video clips lasting 20 sec and including social scenes of adolescents with socially positive and social threatening interactions were presented simultaneously.	Lonely adolescents showed attention bias by fixating more on socially threatening stimuli for the first 2 sec (early attentional hypervigilance) compared to their non-lonely peers. After the initial vigilance, lonely adolescents avoided further fixation on social threats, showing a pattern of attentional disengagement similar to non-lonely adolescents.
8	Cacioppo et al. 2015 USA	Attention Interpretation	70 Mage = 23.59	R-UCLA HADS Words (social and emotional)	EEG	Participants completed 40 trials with social (positive and negative), and non-social (positive and negative) words presented in coloured ink and were instructed to identify the ink colour quickly as possible. Decoding accuracy was also measured.	Lonely adults demonstrated earlier neural differentiation of negative social words from non-social words than non-lonely adults, with heightened activation in extrastriate cortex, prefrontal cortex, and anterior cingulate cortex**.** Positive words triggered brain activity later than negative words and elicited more distributed brain activation patterns in lonely adults than non-lonely adults. Lastly, no significant differences were found in accuracy between lonely and non-lonely adults.

	Author Year Country	Type of cognitive bias	N Age	Measures Material	Experimental technique	Experimental paradigm	Key findings
9	Lodder et al. 2015 Netherlands	Attention	51 18 - 24	UCLA-3 SPIN CES-D Static Images (happy, fear, anger, sad, and neutral) IAPS (social vs non-social) Video clips (positive vs negative interactions)	Eye tracking	*Face task:* Participants viewed 50 images and eye movements were tracked to measure gaze duration and fixations. *Emotion array task:* Participants viewed arrays of 4 faces with different emotions and gaze behaviour was recorded for each emotion. *Social array task:* Participants viewed arrays with positive-social, negative-social, positive-non-social and negative-non-social images. Gaze duration and fixations were tracked. *Video task:* Participants watched 20 video clips (positive and negative) of conversations. Gaze duration and fixations were recorded.	The overt visual attention to facial emotions did not differ significantly between lonely and non-lonely adults. There were no differences between groups in gaze duration or number of fixations on specific face regions. Lonely and non-lonely adults showed similar gaze patterns across emotional expressions. Both groups gazed longer at positive-social images than negative-social ones. All participants showed longer gaze durations on negative clips overall.
10	Cacioppo et al. 2016 USA	Attention Interpretation	19 18 - 44	UCLA-3 IAS CES-D Static Images (social threat vs non-social threat)	EEG	Participants viewed 28 images (social threat, non-social threat, social non-threat, non-social non-threat) displaying for 1000 ms, where they rated the valence of the images quickly and accurately as possible (pleasant or unpleasant).	Lonely adults showed earlier neural differentiation of social threat images from non-social threat images compared to non-lonely adults. However, there was no significant differences in reaction times. Lonely adults also demonstrated earlier increased activation for social threat images in regions linked to attention (dorsolateral prefrontal cortex), emotional processing (amygdala, insula), and threat detection (temporal-parietal junction, anterior cingulate cortex). Lastly, both groups rated social-threat images as more unpleasant than non-social threat images.
11	Lodder et al. 2016 Netherlands	Attention Interpretation	Study 1: 170 Study 2: 130 17 - 27	UCLA-3 SPIN & SPAI-18 CES-D & BDI-II Morphed Videos (angry, sad, fear, happy) Video Clips (real life conversation)	Computerised	Study 1: Participants viewed faces gradually morphed from a neutral to full-intensity emotion in 10 sec and instructed to identify the emotion as quickly and accurately as possible. Study 2: First, participants held two 5-minute conversations with an unfamiliar partner. Gaze behaviour was measured through video recording. Then, they completed the "Reading the Mind in the Eye Test (RMET)" by selecting the correct emotion for photos showing only the eye region.	Loneliness was not associated to overall emotion recognition accuracy or reaction times, but a small positive correlation was found between loneliness and accuracy for recognizing anger in the morph task. Loneliness was associated with longer gaze duration towards the conversation partner's face during the second real-life conversation, but not during the first conversation.

	Author Year Country	Type of cognitive bias	N Age	Measures Material	Experimental technique	Experimental paradigm	Key findings
12	Vanhalst et al. 2017 Belgium	Attention Interpretation	170 13 - 15	LSDQ SASA SMFQ Morphed Videos (happy, sad, fear)	Computerised	Participants completed the emotion recognition task with 36 trials and identified emotions as soon as they detected an emotion. Metrics for accuracy and sensitivity (percentage of morph required for correct identification) were recorded.	Lonely adolescents demonstrated increased sensitivity to negative facial emotions (sad and fear), requiring less emotional intensity compared to positive emotions when depression and social anxiety was controlled. However, loneliness was not significantly associated with overall accuracy in recognizing any facial emotions.
13	Bangee & Qualter 2018 UK	Attention	43 18 - 30	UCLA-3 CES-D BFNE Static Images (neutral, happy, fear, angry) IAPS (social scenes)	Eye tracking	Task 1: 24 picture slides including four emotions were presented at the same time for 8 seconds. Task 2: 16 male face pictures with happy and angry emotions in a crowd were used with varying crowd ratios across 21 slides, each picture was presented for 8 sec. Task 3: 24 picture slides was presented with: (1) physical threat (aggression); (2) social threat (rejection); (3) social positive (social interactions); and (4) neutral (sky) at the same time on the screen for 8 seconds. Data on fixation duration and initial gaze direction were recorded.	Task 1: No differences in fixation time or first fixations between lonely and non-lonely adults for any emotion. Task 2: Lonely adults were more likely to fixate initially on angry faces in a crowd of happy faces compared to non-lonely adults. Task 3: Lonely adults spent significantly longer on social rejection images than non-lonely adults.
14	Shin & Kim 2019 South Korea	Attention	95 Mage = 21.8	UCLA Neuroticism Mood Auditory Stimuli (social vs non-social, positive vs negative words)	Computerised	Participants completed an Auditory Stroop task, where they judged the valence of a word's meaning as quickly and accurately as possible while ignoring the tone of voice.	Lonely adults exhibited a stronger attention bias toward negative vocal tones than positive ones with significantly slower reaction times compared to non-lonely adults. This bias was more pronounced for negative social words even after controlling for neuroticism, mood, and gender.

	Author Year Country	Type of cognitive bias	N Age	Measures Materials	Experimental technique	Experimental paradigm	Key findings
15	Morningstar et al. 2020 Canada	Interpretation	122 11- 18	LAS – CA SAM-CA Auditory Stimuli (anger, disgust, fear, happy, sad, mean, friendly)	Computerised	Participants completed *the Vocal Emotion Recognition Task* and listened to each recording twice via headphones and selected the speaker's intended emotion from seven labelled options using a keyboard.	Lonely adolescents showed interpretation bias with reduced accuracy in recognizing fearful tone, and increased accuracy in recognizing friendly tone.
16	Saito et al. 2020 Japan	Attention	43 21 - 22	UCLA-3 Static Images (face: warm, competent, cold, and incompetent and house)	Eye tracking	Participants completed a face-house task using a target-distractor paradigm. They determined whether two house images (targets) were identical or different while ignoring facial distractors. The task included 20 faces: warm and competent, warm but incompetent, cold but competent, cold and incompetent. The response time, fixation duration on faces and accuracy were measured.	Loneliness did not predict overall attention to faces measured with reaction time; however, high-lonely adults demonstrated increased attention to warm faces compared to competent faces while low-lonely adults focused more on competent faces.
17	Ypsilanti et al. 2020 UK	Attention	Study 2: 80 55 - 90	UCLA-3 SDS STAI-AD GDS Static Images (self and neutral images)	Eye tracking	Participants viewed images of their own face and unknown neutral faces for 5 seconds each in six trials. First fixation (vigilance), fixation duration (maintenance), and fixation duration change (avoidance) patterns were recorded.	Loneliness did not significantly influence gaze behaviour. There were no differences in time to first fixation (vigilance), fixation duration (maintenance), or avoidance patterns when viewing self-images or unknown faces.
18	Cheeta et al. 2021 UK	Attention Interpretation	77 18 - 70	UCLA-3 BDI – II Static Images (happy, sad, fear, anger, disgust, surprise)	Computerised	Participants completed a computerized facial emotion recognition task where emotional stimuli presented for 500 m at different intensities from 0% to 100%, and participants selected emotions from six options.	No significant differences in reaction times between groups for any emotions. Lonely adults demonstrated increased decoding accuracy for sad faces, and decreased accuracy for fear faces. Lonely adults were more likely to misattribute neutral faces as sad.
19	Grenann et al. 2021 USA	Attention	147 18-84	UCLA-3 SD-WISE GAD-7 PHQ-9 Static Images (neutral, happy, sad, angry)	EEG	Participants were instructed to respond to arrows overlaid on faces with different emotions. They completed 144 trials with feedback provided after each response for accuracy.	Lonely adults showed attention bias with slower response time to angry faces. This was supported with increased beta activity in the left superior parietal cortex in lonely adults when angry faces were presented.

	Author Year Country	Type of cognitive bias	N Age	Measures Materials	Experimental technique	Experimental paradigm	Key findings
20	Lau et al. 2021 UK	Interpretation	104 18-24	UCLA-3 GAD-7 PHQ-9 Scenario Vignettes	Computerised	Participants completed *Adolescents Interpretation Bias Task* with ambiguous social and non-social (bodily or health related) scenarios in four time points.	Lonely adults interpreted ambiguous messages as more socially threatening and less socially positive compared to non-lonely participants, particularly at the first time point. Moreover, loneliness predicted more negative interpretations over time, but this effect disappeared after accounting for anxiety and depression. Negative interpretations reinforce concurrent loneliness but do not significantly predict its progression over time.
21	Okruzsek et al. 2021 Poland	Interpretation	252 18 - 50	R-UCLA LSNS Scenario Vignettes	Computerised	Participants completed t*he DACOBS Attribution Bias* subscale and The Ambiguous Intentions *Hostile Questionnaire* by rating the likelihood that the behaviour in the scenario was intentionally hostile.	Loneliness was both a driver and a consequence of interpretation bias, more specifically hostile interpretation bias. Lonely adults rated ambiguous social scenarios more hostile.
22	Saporta et al. 2021 Israel	Approach-Avoidance	479 24 - 78	UCLA-3	Computerised	Participants completed *"Interpersonal Distance Task"* measuring real-time social approach and avoidance responses. They were instructed to imagine themselves standing in a virtual room and either being approached either by a stranger or a friend or approaching them. Response times were recorded, and faster responses indicate preference for greater distance (greater avoidance).	Chronic loneliness was associated with greater avoidance (preference for greater interpersonal distance) while situational loneliness led to greater approach motivation. Moreover, being approached resulted in greater social avoidance (larger interpersonal distance) in lonely adults compared to actively approaching.
23	Du et al. 2022 China	Attention	30 17 - 29	UCLA-3 Static Images (social vs non-social, faces, and images of buildings)	EEG	Participants performed a *"Category judgment task"* with 90 trials to identify whether a "probe" image matched the "target" image (social vs non-social stimuli) as quickly as possible. Reaction times and brain activity were measured.	Lonely adults demonstrated attention bias towards negative faces with significantly faster reaction times than neutral and positive ones compared to non-lonely adults. Neurophysiological evidence showed early visual attention in the left hemisphere with significantly higher P100 amplitude and faster facial decoding with significantly shorter N170 latency for negative faces in lonely adults.

	Author Year Country	Type of cognitive bias	N Age	Measures Materials	Experimental technique	Experimental paradigm	Key findings
24	Nombro et al. 2022 Canada	Interpretation	Study 1: 111 Study 2: 222 Mage= 21.8 Mage= 43.63	SELSA-S PHQ-9 GAD-7 Scenario Vignettes	Computerised	Participants completed *"Ambiguous Scenario Test for Depressed Mood" (AST-D)* where they read ambiguous scenarios and were asked to imagine an outcome. They were then asked to rate the pleasantness and vividness of each outcome.	*Socially* lonely adults showed interpretation bias in which they rated ambiguous scenarios more negative than pleasant compared to non-lonely adults even when controlling for depression, anxiety and vividness. However, romantic and family loneliness were not significant predictors of interpretation bias.
25	Smith et al. 2022 USA	Attention Interpretation	122 21 - 33	UCLA-3 Video Clips (happy, sad, angry, pain)	Computerised	64 ten-second videos were shown, and participants were asked to identify the emotion. Reaction times and accuracy were measured and analysed by using signal detection statistics. Data was collected in six time points over three years.	Increases in loneliness were associated with decreases in reaction times for correctly identifying sad emotion; decreased accuracy in discriminating angry and sad faces from other facial emotions, indicating reduced sensitivity; and increases in mislabelling faces as anger or pain.
26	Smith & Pollak 2022 USA	Approach-Avoidance	74 18 - 46	UCLA (3-item) Images and Auditory Stimuli	ECG	Participants completed Pavlovian approach-avoidance task where coloured shapes were paired with positive (e.g., rewards) or negative reinforcers (e.g., aversive noise). They chose whether to approach (green button) or avoid (red button) these stimuli based on prior conditioning. Their PNS activity was recorded.	Lonely adults with higher resting PNS activity demonstrated greater to approach behaviour both positive and negative stimuli. Conversely, lonely adults with lower PNS activity did not show such motivational increase, meaning loneliness alone did not predict approach behaviour.
27	Maka et al. 2023 Poland	Attention	52 18-35	R-UCLA CESD-R Static Images (angry/neutral or neutral/neutral)	EEG	Participants completed a dot-probe task, where they responded to the orientation of a target after viewing pairs of faces. Reaction times and accuracy were recorded over 720 trials. EEG was used to measure the N2pc component, indicating attentional orienting.	Lonely adults did not differ from non-lonely adults in reaction times, accuracy and N2pc component. However, they had lower drift rates indicating reduced perceptual sensitivity (decision-making inefficiency) and higher drift rate variability indicating greater instability (unstable decision making), suggesting general perceptual decision-making inefficiency in loneliness.
28	Grocott et al. 2024 Canada	Interpretation	591 18-53	UCLA-3 GAD-7 CESD-R Static Images (social, non-social, ambiguous)	Computerised	Participant completed *the Valence Bias Task* with 192 images (facial emotions, gestures or body language). State loneliness was induced via the writing task on personal experience and false feedback.	State loneliness was associated with more positive interpretations, especially for non-social ambiguous stimuli after induction compared to chronic loneliness. Chronic loneliness was *not* associated with interpretation bias in ambiguous social or non-social images.

3.2. Narrative Results

Cognitive biases in loneliness have been extensively investigated in the literature, including different experimental techniques, paradigms, measures, diverse materials, and various age groups. These studies showed that age is a crucial factor in studying attentional processes as they develop from childhood to adulthood. However, in this review, grouping according to age categories was challenging, taken that some studies included a broad adult age range (e.g., 18–84 years), while others specifically focused on young adults (18–30 years), or middle-aged and older adults (55–90 years). Given the inconsistency in age categorisation across the studies, all participants over the age of 18 was treated as a single adult group. In contrast, individuals aged 8 to 17 years were grouped together as children and adolescents, following typical developmental distinctions (e.g., Diaz et al., 2021), to capture key cognitive changes that may occur prior to adulthood and to ensure that developmental differences in cognitive biases were considered.

3.2.1. Attention Bias

The findings on attention bias have been categorised based on the measurement type: *reaction time, eye tracking, and brain activity*. This classification enabled us to see if various measures pinpoint distinct aspects of attention bias. For instance, while both *reaction time* and *eye tracking* are behavioural measures; *reaction time* provides discrete measures of cognitive processing speed and covert attention allocation, whereas *eye tracking* captures continuous, spatial-temporal patterns of overt attention and visual processing (Holmqvist et al., 2011). Moreover, while some biases may be detected in neural signals, they might not be reflected in the behavioural measures used.

Children and adolescents (8 – 17 years old): Only one study to date has examined attention bias in lonely children, and just two studies have explored this mechanism in adolescents. According to findings from the *eye-tracking* study, lonely children displayed initial longer fixation time on socially threatening stimuli as presented in video clips of negative social interactions, and disengagement from those rejection stimuli took longer compared to their non-lonely counterparts, demonstrating sensitivity to social threats (Qualter et al., 2013). Bangee et al. (2014) reported that similar to lonely children, lonely adolescents also demonstrated initial fixation on socially threatening stimuli, but unlike lonely children, they avoided further fixation and showed similar attentional disengagement as non-lonely adolescents. Vanhalst et al. (2017) also reported that lonely adolescents demonstrated attention bias to negative facial emotions, as evidenced by their increased sensitivity measurements, accuracy in sad and fear faces compared to happy faces at lower morph intensities (indicating shorter reaction time).

Adults (18 – 90 years old): Lonely adults exhibited a complex pattern of responses, which are outlined below with respect to the measurement type included.

i. ***Reaction time:*** Several studies did not find any attention bias in lonely adults. For instance, Lodder et al. (2016; morphed videos of facial emotions); Cheeta et al. (2021; static images of facial emotions); Saito et al. (2020; static images of houses and faces); and Cacioppo et al. (2016; static images of social situations), found no evidence of any attention bias in loneliness. However, contradictory to these findings, Grennan et al. (2021) and Du et al. (2022) both found attention bias to static images of negative faces with reduced reaction times (indicating

quicker reaction) than neutral and positive faces compared to their non-lonely counterparts. Furthermore, Smith et al. (2022) found attention bias to video clips of negative faces (e.g., sad) with reduced reaction times compared to other emotions. In addition to this, Gardner et al. (2005) stated that lonely adults demonstrated increased attention to vocal tones regardless of the valance compared to non-lonely adults, meanwhile, Shin and Kim (2019) found similar results, but in their experiment, lonely adults were particularly more hypervigilant to negative social vocal tones with reduced reaction times.

ii. ***Eye tracking:*** Lodder et al. (2015) and Ypsilanti et al. (2020) did not find any attention bias to facial and social images among lonely adults, respectively. In addition, Bangee and Qualter (2018) did not find attention bias to facial emotions among lonely adults in the first task, however they found attention bias with initial fixation to angry faces compared to happy faces and increased fixation duration time to social rejection images compared to non-lonely adults in other tasks. On the other hand, Saito et al. (2020) found increased attention with longer fixation time to warm faces compared to competent faces among lonely adults.

iii. ***Brain activity:*** In their EEG studies, Cacioppo et al. (2015) found that lonely adults demonstrated earlier neural differentiation of negative social words from negative non-social words with heightened activation in brain regions linked to attention (e.g., extrastriate cortex, prefrontal cortex, anterior cingulate cortex). Similarly, Cacioppo et al. (2016) reported earlier neural differentiation of social threat images from non-social ones compared to non-lonely counterparts with increased early activation in amygdala, insula dorsolateral prefrontal cortex,

temporal-parietal junction and anterior cingulate cortex. According to an fMRI study, Cacioppo et al. (2009) found reduced activation in the ventral striatum (a brain region associated with reward processing) for positive social stimuli compared to positive non-social stimuli and greater activation in the bilateral visual cortex in response to negative social stimuli compared to negative non-social stimuli in lonely adults when non-lonely adults. Moreover, Du et al. (2022) found early visual attention in the left hemisphere to negative faces in lonely adults. Along with this, Kanai et al. (2012) found reduced grey matter volume in the left posterior superior temporal sulcus (pSTS) in lonely individuals in facial emotion processing task, linking structural brain differences to deficits in gaze perception and highlighting a potential neural basis for social attention biases in loneliness. Grennan et al. (2021) also found increased beta activity in the left superior parietal cortex for negative faces (e.g., angry) among lonely adults. Finally, Maka et al. (2023) found no attention bias towards any facial emotions in lonely adults, instead loneliness was associated with reduced perceptual sensitivity, reflected in lower drift rates, and greater decision variability, indicated by higher drift rate variability, suggesting a broader inefficiency in cognitive processing rather than heightened attention towards negative stimuli.

3.2.2. Interpretation Bias

Children and adolescents (8 – 17 years old): There were only two experimental studies in the literature investigating interpretation bias in children and adolescents, yielding mixed results. While Vanhalst et al. (2017) did not find any interpretation bias in lonely children in terms of overall facial emotion recognition, Morningstar et al. (2020)

reported that lonely adolescents demonstrated reduced accuracy in recognising negative (fearful) emotion, but increased accuracy identifying positive (friendliness) in auditory expressions.

Adults (18 – 90 years old): Based on experimental studies investigating the interpretation bias, we found a recurring finding across multiple studies in adults. Lonely adults typically interpreted ambiguous scenarios and messages more negatively, making interpretations such as rejection, threat, hostility, or insult, compared to their non-lonely counterparts (Edwards et al., 2001; Lau et al., 2021; Okruzsek et al., 2021; Nombro et al., 2022). In terms of interpreting facial emotions, some studies reported increased accuracy to negative emotions compared to positive ones (e.g., angry, sad; Lodder et al., 2016; Cheeta et al., 2021); one study indicated decreased accuracy in discriminating angry and sad faces from other emotions (Smith et al., 2022); while two studies did not find any significant difference in emotion recognition (Kanai et al., 2012; Lodder et al., 2016). Yet, one study reported generally higher accuracy in identifying emotions in faces with low emotional intensity (Gardner et al., 2005), while another study found that lonely adults have overall lower accuracy in facial emotion recognition (Zysberg, 2012). Moreover, some studies reported a tendency to misinterpret neutral facial expressions as negative among lonely adults (e.g., sad, anger, pain; Cheeta et al., 2021; Smith et al., 2022). Interestingly, one study reported that interpretation bias varied by loneliness type: state loneliness has been linked to more positive interpretations, particularly for non-social ambiguous images, whereas chronic loneliness showed no interpretation bias towards either social or non-social images (Grocott et al., 2024). However, two studies found no evidence of interpretation bias in response to social

images (Cacioppo et al., 2009; Cacioppo et al., 2016), another reported no bias towards either social or emotional words in loneliness (Cacioppo et al., 2015).

3.2.3. Approach-Avoidance Bias

Only two experimental studies were found that investigated approach-avoidance biases in loneliness up to now. Both studies suggested that lonely individuals demonstrated conflicted motivations, showing both increased engagement with rewarding stimuli (Smith & Pollak, 2022) and heightened avoidance (Saporta et al., 2021), providing evidence for the context-dependent nature of approach-avoidance behaviour in lonely individuals. Saporta et al. (2021) reported that chronic loneliness was associated with greater social avoidance (preference for greater interpersonal distance), while situational loneliness was associated with smaller interpersonal distance, indicating approach motivation. These findings suggest that transient loneliness can enhance the drive for social connection, unlike chronic loneliness. Moreover, lonely adults displayed greater avoidance when being approached (passive condition) compared to when they were the ones actively approaching others. Similarly, Smith & Pollak (2022) found that lonely adults with higher parasympathetic nervous system (PNS) activity showed increased approach motivation and decreased avoidance behaviour regardless of whether the reinforcer was rewarding or aversive, suggesting a heightened engagement with socially relevant cues regardless of valence and more adaptive profile. In contrast, lonely adults with lower PNS activity did not show this motivational shift.

4. Discussion

The current scoping review synthesised findings from 28 experimental studies investigating cognitive biases in loneliness, specifically focusing on *attention, interpretation, and approach avoidance biases* within the framework of Social Information Processing (Crick, 1995) and Cacioppo's Evolutionary Model of Loneliness (Cacioppo & Hawkley, 2009).

Across studies, *attention bias* showed mixed results; however, brain imaging appears to be the most reliable measure to detect attention bias. In adult group, neuroimaging studies indicated heightened neural responses to negative social stimuli, particularly in regions linked to attention and threat processing (e.g., amygdala, anterior cingulate cortex and prefrontal regions), and earlier neural differentiation of negative social stimuli (Cacioppo et al., 2015; Cacioppo et al., 2016; Du et al., 2022; Grennan et al., 2021). While EEG and fMRI studies consistently demonstrated evidence of attention bias in loneliness through early neural vigilance to social threat cues, behavioural paradigms such as reaction time and eye-tracking produced more variable results. Across the thirteen behavioural studies (several of which included more than one attention task), eight studies indicated an attention bias, demonstrated by reduced reaction times to negative cues and longer or initial fixations on threat showing hypervigilance, while seven tasks reported no such effects. It is important to note that these behavioural tasks varied widely in their stimuli, including static facial images, morphed dynamic faces, non-social and social scenes, and even vocal tones. Even so, these findings suggest that loneliness primarily manifests as a *covert attentional sensitivity* rather than *overt behavioural bias*. This might be because behavioural paradigms rely on consciously

regulated responses influenced by cognitive control (Gratton et al., 2018; Kunde et al., 2012). This dissociation may reflect that loneliness involves automatic hypervigilance at the neural level, even when overt attention appears unbiased.

The findings in children and adolescents on how loneliness influences attentional processes suggest an initial hypervigilance to socially threatening stimuli in lonely children, with prolonged fixation on negative cues and difficulty to disengage from them (Qualter et al., 2013); while lonely adolescents are similarly drawn to negative social cues initially but unlike children, they demonstrate quicker disengagement, avoiding further fixation on social threat stimuli (Bangee et al., 2014). This transition might reflect developing adaptive regulatory mechanisms in social interactions, where lonely adolescents gradually learn to tune out or suppress attention to social negativity as a coping strategy. However, it is important to note that studies on children and adolescents are sparse. These shortcomings are relevant to point out taken how critical childhood is in forming social skills (Sørlie et al., 2021).

Meanwhile, *interpretation bias* emerged as the most consistent cognitive bias of loneliness, particularly in adult group, across the fourteen studies. Approximately 67% of the studies reported that lonely adults consistently interpret ambiguous social information more negatively, perceiving them as threatening, hostile, or rejecting (Edwards et al., 2001; Lau et al., 2021; Okruzsek et al., 2021; Nombro et al., 2022); or a tendency to misattribute neutral expressions as negative emotions (Cheeta et al., 2021; Smith et al., 2022). These findings suggest that biases are more pronounced when facing ambiguous stimuli, when the participant experiences uncertainty that requires interpretation, which is consistent with previous findings in the literature (Bengtsson et al., 2011; Sharot et al., 2012). A smaller subset of studies revealed heterogeneous

outcomes in decoding accuracy for emotional expressions. Some studies found heightened sensitivity to negative emotions (e.g., anger, sad; Lodder et al., 2016; Cheeta et al., 2021), whereas others showed no differences (Kanai et al., 2012; Lodder et al., 2016) or overall reduced accuracy in decoding emotions among lonely individuals (Zysberg, 2012). This variation suggests that task design (static vs. dynamic faces, valence range, and intensity levels) may strongly influence results. Nevertheless, not all findings point towards uniform negativity. For instance, Grocott et al. (2024) introduced an important distinction between situational and chronic loneliness: situational (state) loneliness elicited *more positive interpretations*, especially for non-social ambiguous stimuli, whereas chronic loneliness showed no such bias. The result refines the loneliness paradox by showing that interpretation biases may depend not only on *what* individuals perceive but *how long* they have experienced loneliness. Lau et al. (2021) found that when the feeling of loneliness is chronic, the interpretation bias seen in situational loneliness is better explained by depression and social anxiety symptoms. This raises the question of whether co-occurring symptoms play a more significant role in maintaining cognitive biases in chronic loneliness. Further research is needed to explore the role of these coexisting mental health conditions which are correlated with loneliness to answer this question.

Interestingly, neuroimaging studies found no evidence of interpretation bias in response to social stimuli (Cacioppo et al., 2009; Cacioppo et al., 2016; Cacioppo et al., 2015), suggesting that neural differentiation does not always translate into biased interpretation. Moreover, the two studies on interpretation bias in children and adolescents reveal inconsistent findings, highlighting a major gap in understanding how loneliness shapes social-cognitive development. However, due to the scarcity of studies,

it remains unclear whether these differences represent a consistent pattern or are specific to certain experimental paradigms.

Meanwhile, the limited findings from two studies on the *approach-avoidance bias* revealed crucial distinction of the dual nature of loneliness based on its chronicity. Saporta et al. (2021) found that chronic loneliness is associated with greater social avoidance, such as maintaining larger interpersonal distance. Conversely situational loneliness had the opposite association with interpersonal distance preferences, reflecting greater approach tendencies. This pattern supports the evolutionary theory of loneliness in which loneliness situational loneliness promotes desire for reconnection, while chronic loneliness drives people to withdrawal from social interactions. The study further showed that lonely adults were more avoidant when others approached them (passive condition) compared with when they themselves initiated approach, underscoring the asymmetry in perceived relational risk. Interestingly, in the other study, lonely adults with higher PNS activity demonstrated a clear shift towards greater approach and reduced avoidance for both positive and negative stimuli (Smith & Pollak, 2022). This pattern might suggest that lonely individuals with stronger physiological regulation may engage with socially, possibly reflecting more adaptive motivational profile. Taken together, these results point to PNS activity as a key moderator of how loneliness translates into motivational tendencies, and they highlight the importance of considering physiological regulation in loneliness.

Consequently, the approach-avoidance bias in loneliness is a particularly attractive model behaviour to investigate in conjunction with time, physiological reactivity, and co-occurring symptoms, in order to understand the paradox of a simultaneous drive for social connection and negative expectations. The dual effect of approach and avoidance

suggests that effective interventions for loneliness should consider both enhancing social motivation (to encourage social engagement) and reducing avoidance tendencies (to lessen the fear of rejection and social threat sensitivity).

Despite these promising directions, a key methodological challenge remains. Currently, there is no adopted, psychometrically validated and reliable scale measuring situational loneliness, except COVID-19-specific questionnaires, such as Loneliness and Isolation during Social Distancing (LISD; Gründahl et al., 2022). LISD was developed specifically for the COVID-19 pandemic context, hence it has limited applicability. This conceptual and methodological gap is particularly problematic given that there is emerging evidence suggesting various forms of loneliness may involve distinct cognitive and behavioural mechanisms (Saporta et al., 2021).

On the other hand, this scoping review has its limitations. It includes studies which varied in how loneliness was measured, trait vs. state, single-item vs. validated scales, use of different psychometric scales, and how cognitive biases were operationalised, e.g., diverse paradigms such as Stroop tasks, eye-tracking, scenario vignettes or neuroimaging techniques. This heterogeneity limits the direct comparability of findings across studies and could contribute to the inconsistent results observed, particularly for attention bias. Secondly, given the heterogeneity of experimental designs, we employed narrative and thematic synthesis rather than quantitative analysis.

We argue that the loneliness paradox; the co-occurrence of a drive for connection and social withdrawal, remains central, and should guide developmental and clinical considerations for research and interventions. Future research should prioritise: (1) increased inclusion of children and adolescents in addition to adult sample in experimental research to compare changes across development; (2) integration of

behavioural, neural, and physiological data; (3) research investigating approach-avoidance bias to fill the methodological, empirical, and evidence gaps; (4) ecologically valid paradigms simulating real-world social experiences, such as immersive VR environments; (5) examining the distinction between chronic and situational loneliness using longitudinal and multi-method approaches.

5. Conclusion

The Evolutionary Theory of Loneliness suggests that lonely individuals develop cognitive biases towards emotional and social cues which perpetuate their loneliness. In this current review, we examined these cognitive biases, *attention, interpretation* and *approach-avoidance*, in experimental studies through the lens of Social Information Processing framework. The findings reveal that loneliness is not only an emotional state but a condition with measurable cognitive and behavioural correlates that shape how individuals perceive, interpret, and respond to social information. Despite extensive research, the empirical evidence remains inconsistent depending on the paradigm, stimuli, measures, and age groups. Overall, the evidence suggests that loneliness selectively distorts cognitive and motivational systems involved in social information processing. While attention and interpretation biases contribute to threat sensitivity and social misperception, approach–avoidance conflict reflects the behavioural outcome of this distorted processing, capturing the essence of the *loneliness paradox*. Overall, these findings underscore the importance of developing Cognitive-Behavioural Modification (CBM) interventions that *target attention, interpretation,* and *approach-avoidance* biases, to disrupt the self-reinforcing cycle of loneliness and promote more adaptive social engagement.

CHAPTER 3

STUDY 2

Multivariate Modelling of Loneliness: Sociodemographic and Psychological Predictors

"All models are wrong, but some are useful." - George Box
(Loneliness may not be fully captured in β values, but in modelling it, we begin to understand)

Chapter Introduction

Meaningful relationships are built on a foundation of emotional contingency, trust, social engagement, cognitive flexibility and adaptability (Block et al., 2022; Mellor et al., 2008). When these elements are present, they foster deep connections and provide a sense of belonging and emotional fulfilment (Mellor et al., 2008). These relationships are not only satisfying but are also critical to mental and emotional well-being, as they offer a sense of connection, validation, and stability (Wissing et al., 2021). When these foundational components are disrupted or absent, individuals may experience persistent feelings of disconnection and loneliness (Motta, 2023). Hence, loneliness is more than a number on a scale; it is an experience shaped by emotional, behavioural, cognitive, and social factors.

To better understand the underlying mechanisms of this experience, the following empirical studies were conducted through a multivariate modelling approach to examine how sociodemographic characteristics and psychological predictors contribute to loneliness.

Study 2a explored the sociodemographic predictors of loneliness, including biological sex, age, relationship status, living condition, employment status, education level, and ethnicity, to identify which population groups may be at greater risk of experiencing loneliness.

Study 2b focused on psychological predictors, specifically depression, social anxiety, and alexithymia, to investigate how these constructs contribute to loneliness through direct, mediating, and moderating pathways.

Study 2c focused on behavioural and social predictors to explore how cognitive and behavioural avoidance mediate the well-established depression–loneliness relationship and how trust moderates the strength of this association.

Together, these studies provide an integrated understanding to explain the complex phenomenon loneliness by examining its sociodemographic, cognitive, psychological, behavioural, social and interpersonal determinants, offering a foundation for the design of next experiments in this thesis[2].

[2] *In the present chapter, analyses of the data are presented to explore sociodemographic and psychological predictors of loneliness. The data were originally collected as part of other research projects included in other chapters of this thesis (Chapter 4, 5 and 6). Each study was conducted under separate ethical approvals granted by the University of East Anglia School of Psychology Research Ethics Committee. Each project was preregistered on the Open Science Framework (OSF) prior to data collection. Full details of the specific ethics approvals and OSF registrations are provided in the corresponding methods sections of each study chapter where the full experiments are reported. All procedures adhered to the ethical standards set by the American Psychological Association (2017), the Declaration of Helsinki (World Medical Association, 2013), and the University's Research Ethics Code of Practice.*

Study 2a

Sociodemographic Predictors of Loneliness

1. Introduction

Loneliness is a universally widespread complex phenomenon influenced by psychological, neurobiological, cognitive and social factors, but also sociodemographic characteristics (Cacioppo & Cacioppo, 2018). There is growing body of research indicating that variables such as age, gender, socioeconomic level and cultural orientation are associated with differences in prevalence and severity of loneliness (Fierloos et al., 2021; Cacioppo & Cacioppo, 2018; Hawkley & Capitanio, 2015). Consequently, understanding how these sociodemographic factors relate to loneliness is crucial for identifying vulnerable populations and informing targeted interventions for public health.

In Chapter 1, it was argued that age is a major risk factor for loneliness and different life stages bring distinct developmental vulnerabilities. In terms of prevalence in different age groups, loneliness appeared to follow a complex, often nonlinear pattern across the lifespan, with varying findings influenced by using different measurement tools for loneliness (Panayiotou et al., 2023). In a comprehensive literature review (Panayiotou et al., 2023), it was concluded that gender differences in loneliness are widely studied but the association between loneliness and gender remains inconclusive. Some studies reported men as the lonelier gender (Maes et al., 2019a), whereas others indicated higher loneliness in women, especially in older age (Nicolaisen & Thorsen, 2024). In terms of education, previous research consistently reported a negative

relationship between education level and loneliness (Beller, 2024; Hutten et al., 2021a; Steed et al., 2007). Moreover, living alone was also consistently reported as a significant risk factor for loneliness, especially in older adults (Chow et al., 2021; Fierloos et al., 2021). Regarding marital status, most studies reported that single, widowed, or divorced participants demonstrated higher level of loneliness (Mishra et al., 2023; Kislev, 2022).

Therefore, the current study sought to explore a series of research questions (RQs) examining the relationships between key sociodemographic variables, specifically biological sex, age, relationship status, living condition, ethnicity, employment status and loneliness. The results from this study established a foundational background for more complex psychological models explored in the subsequent sections of this chapter.

RQ1. Does loneliness significantly differ based on biological sex?

RQ2. Does loneliness significantly differ across age groups (young, middle-aged, and older adults)?

RQ3. Does loneliness significantly differ based on relationship status (e.g., single, married, divorced, separated)?

RQ4. Does loneliness significantly differ based on living arrangement (e.g., living alone, with family, or with a partner)?

RQ5. Does loneliness significantly differ based on employment status?

RQ6. Does loneliness significantly differ based on education level?

RQ7. Does loneliness significantly differ based on ethnic background?

2. Methods

2.1. Participants

A total of 580 adult participants (M_{age} = 37.49, *SD* = 18.19, ranged from 18 to 83 years, 396 female) were recruited for this online study using both Gorilla Experiment Builder (Anwyl-Irvine et al., 2020) and Qualtrics (Qualtrics, Provo, UT). Demographic characteristics of participants and descriptive statistics are presented in Table 5.

Table 5. Participant Demographics and Descriptive Statistics (*N* = 580)

Age Mean (+/- SD)	37.49 (18.19)	***Relationship status***	
Sex		*Single*	126 (21.7%)
Female	396 (68.3%)	*In a relationship*	198 (34.1%)
Male	184 (31.7%)	*Married*	184 (31.7%)
Employment		*Separated*	40 (6.9%)
Student	189 (32.6%)	*Divorced*	32 (5.5%)
Part-time employed	82 (14.1%)	***Living condition***	
Full-time employed	128 (22.1%)	*Alone*	113 (19.5%)
Self-employed	65 (11.2%)	*With parents*	63 (10.9%)
Homemaker	25 (4.3%)	*With other family members*	47 (8.1%)
Retired	72 (12.4%)	*With friends or shared house*	169 (29.1%)
Unemployed	19 (3.3%)	*With partner/husband/wife*	188 (32.4%)
Education level		***Ethnicity***	
Middle school	5 (1.2%)	*White*	434 (74.8%)
Highschool	238 (55.3%)	*Black or Black British African*	46 (7.9%)
Bachelor's degree	129 (30.0%)	*Asian or Asian British - Indian*	32 (5.5%)
Master's degree	45 (10.5%)	*Chinese*	27 (4.7%)
PhD	13 (3.0%)	*Mixed - White and Asian*	26 (4.5%)
		Mixed-White and Black African	15 (2.6%)

2.2. Measures

Demographic variables: All participants completed a questionnaire to collect socio-demographic variables on biological sex, age, level of education, employment status, relationship status, living condition and ethnicity.

Loneliness: The UCLA Loneliness Scale (Version 3; Russell, 1996) was used to measure participants' level of loneliness. The instrument consists of 20 items (e.g., "How often do you feel left out?"). Responses vary on a scale from 1 (*never*) to 4 (*often*) and are scored continuously as the instrument does not provide validated cut-off points. Total scores range from 20 to 80. Internal consistency in this sample was excellent (α= .93).

2.3. Study Design and Analysis

The study employed a cross-sectional, between-subject design. To examine differences in loneliness across demographic variables, a series of one-way ANOVAs were conducted, each corresponding to a single categorical predictor with levels. When significant omnibus effects were observed, post hoc comparisons were performed using Tukey's HSD tests. The data were analysed using RStudio (Posit, PBC, 2024).

3. Results

Sex: There was no statistically significant difference in loneliness between females and males, F (1, 578) = 0.59, p = .443.

Education: The results indicated no statistically significant effect of education level on loneliness, F (4, 575) = 1.05, p = .383.

Ethnicity: The analysis revealed no significant main effect of ethnicity on loneliness, F (6, 573) = 1.54, p = .163.

Age group: Age groups were categorised into three groups based on Halloran's (2024) adult-development framework: Young (18–39), Middle-aged (40–64), and Older adults (65+). The results revealed a statistically significant effect of age group on loneliness, F (2, 577) = 13.33, p < .001. Tukey post hoc tests indicated that participants in the Older group reported significantly lower loneliness than both the Young (p < .001) and Middle-aged (p < .001) groups. There was no significant difference between the Young and Middle age groups (p = .83; Figure 17).

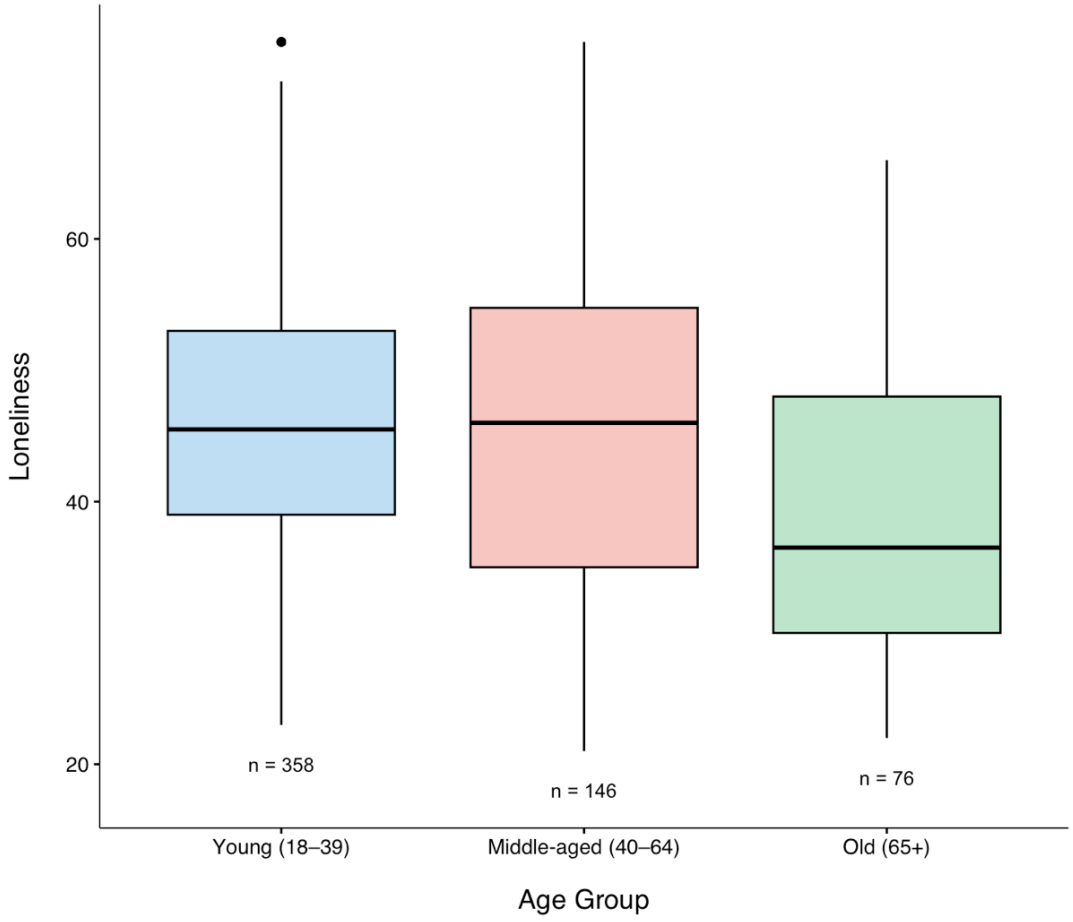


Figure 17. Boxplot of Loneliness Scores Across Three Age Groups
Young (18–39), Middle-aged (40–64), and Older Adults (65+)

Relationship status: The analysis revealed a statistically significant effect of relationship status on loneliness, F (4, 575) = 12.80, p < .001. Post hoc Tukey tests revealed that separated and single individuals reported significantly higher loneliness than married individuals (both p < .001), and those who were married reported significantly lower loneliness than those in a relationship (p = .008). No other group differences were statistically significant (p > .05; Figure 18).

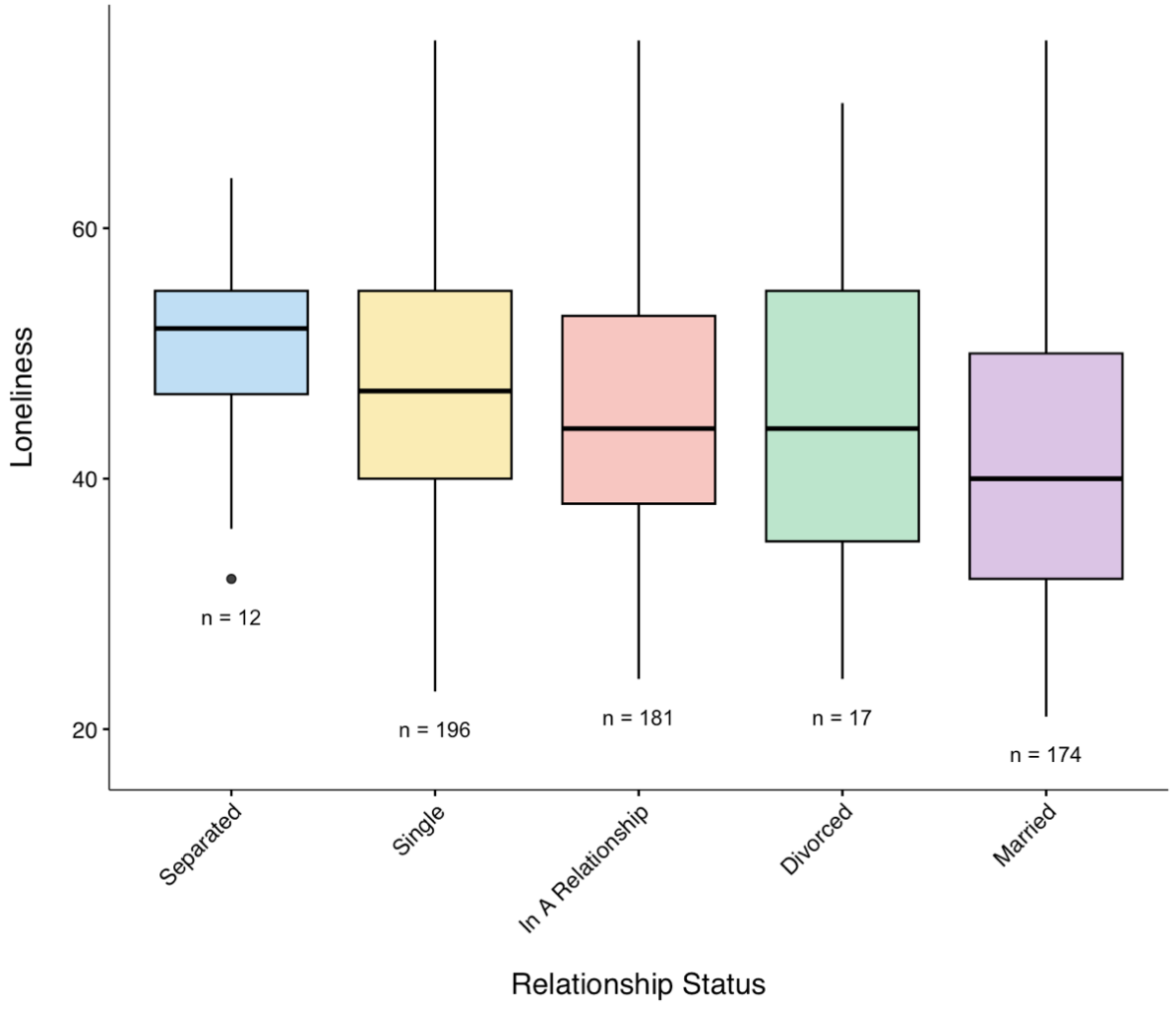


Figure 18. Distribution of Loneliness Scores by Relationship Status.

Living condition: The findings showed a significant effect of living condition on loneliness, F (4, 575) = 7.66, p < .001. Tukey post hoc tests revealed that participants living alone (p < .001) and those living with friends or in a shared housing (p = .003) reported significantly higher loneliness than those living with a partner or spouse. No other group differences were statistically significant (Figure 19).

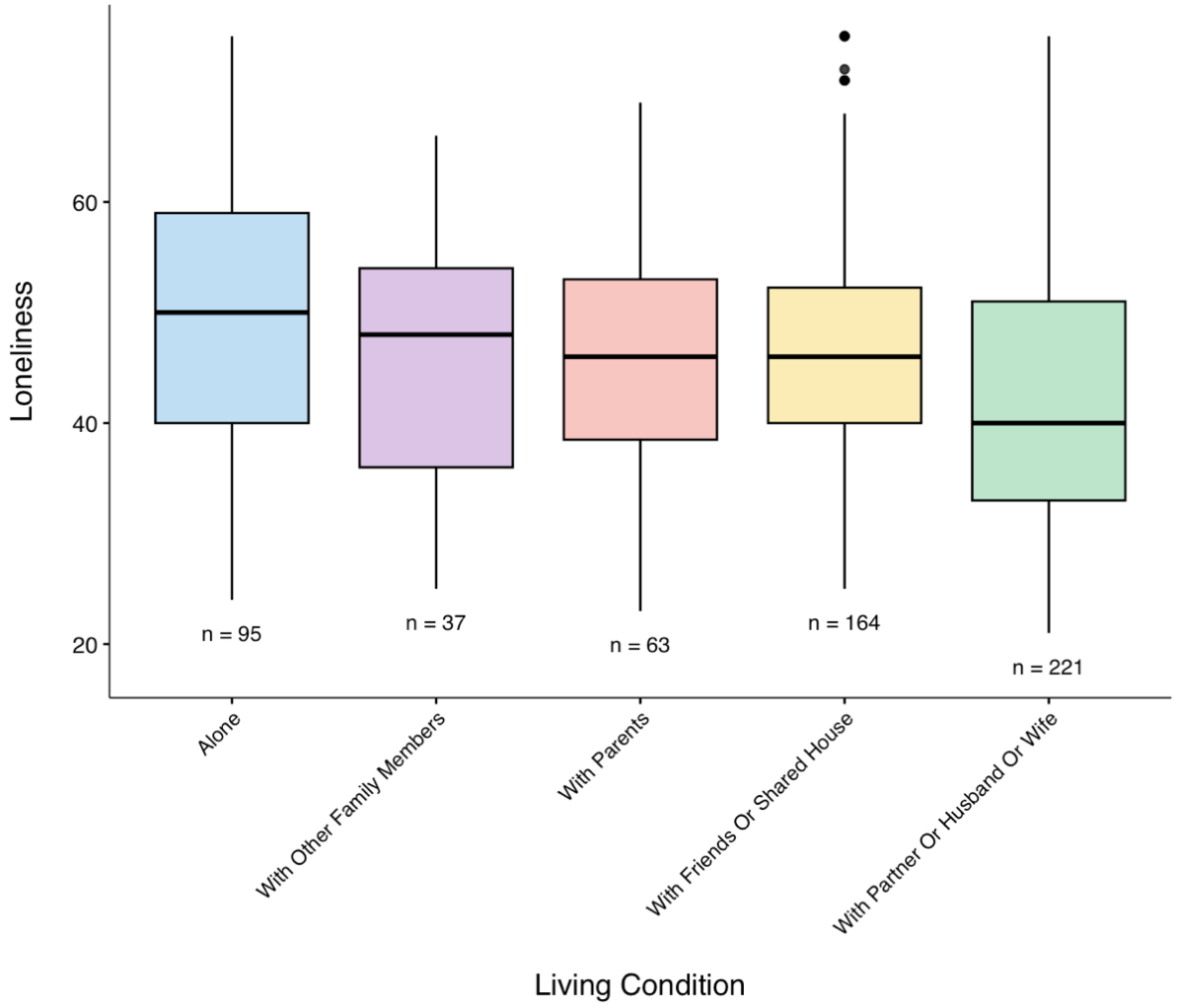


Figure 19. Distribution of Loneliness Scores across Living Condition.

Employment: The analysis revealed a statistically significant effect of employment status on loneliness, F (6, 573) = 4.70, p < .001. Tukey post hoc comparisons indicated that individuals who were retired reported significantly lower loneliness than those who were homemakers (p = .009) and part-time employed (p = .003). In contrast, students (p = .001) and unemployed individuals (p = .005) reported significantly higher loneliness compared to those who were retired (Figure 20).

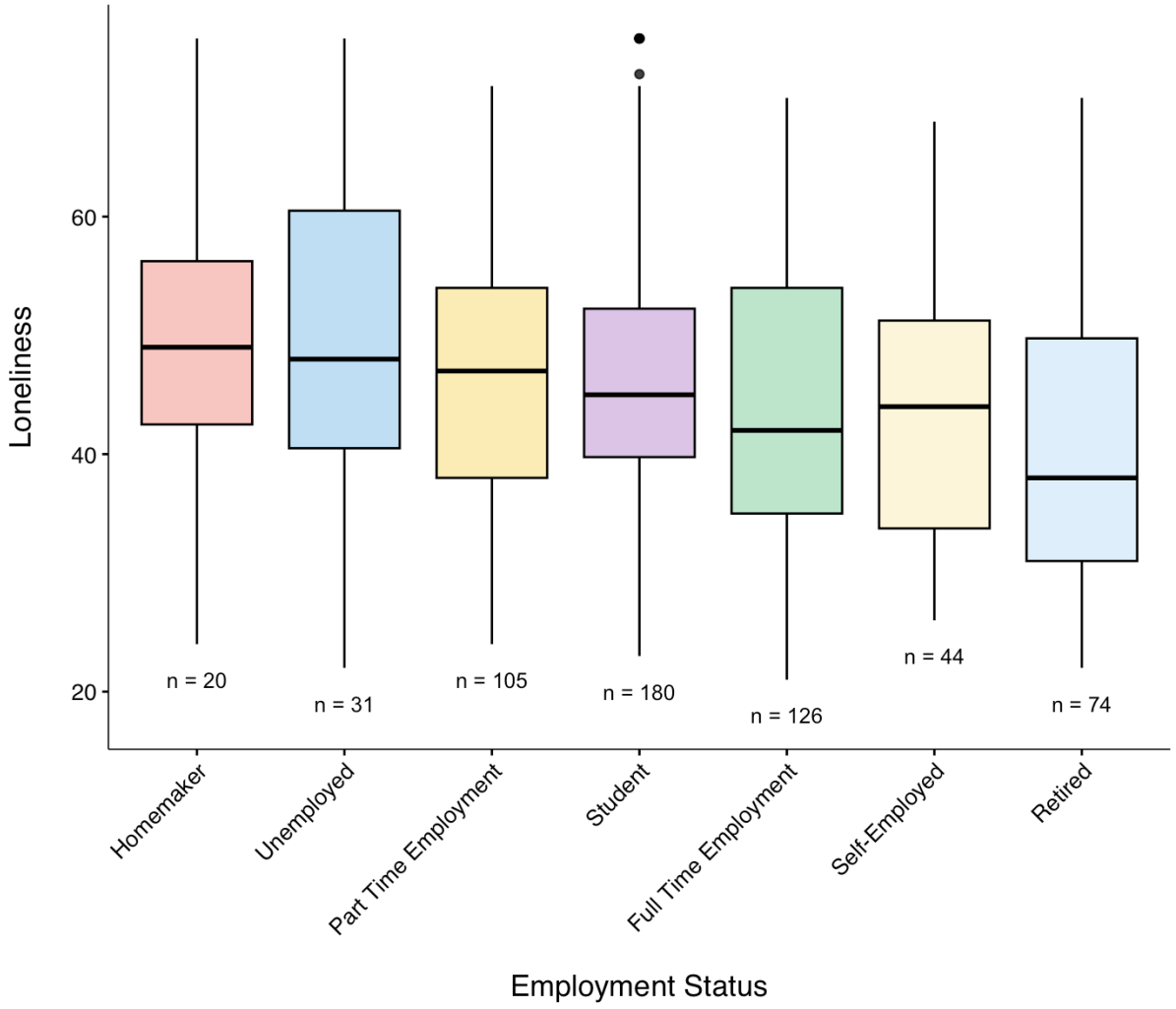


Figure 20. Distribution of Loneliness Scores across Employment Status.

4. Discussion

The current study aimed to explore the role of sociodemographic factors in understanding loneliness within a diverse adult sample. The findings indicated that age, living condition, relationship status and employment status were significant factors of loneliness while biological sex, education level and ethnicity did not show any significant effects.

In terms of age, young adults reported the highest levels of loneliness whereas older adults had the significantly lower levels of loneliness. This finding supports previous research suggesting that loneliness may peak in early adulthood due to transitional life stressors as discussed in Chapter 1 (e.g., identity formation, career pressure, instability in relationships and living situations; Branje et al., 2021; Shovestul et al., 2020) and then decline in older age due to enhanced emotion regulation skills and reduced social expectations (Barreto et al., 2021; Qualter et al., 2013). However, this finding also contradicts with other studies reporting U-shaped trajectory in which loneliness increases again in later life (Graham et al., 2024; Yang & Victor, 2011). Nonetheless, it is important to note that the older age group in this study was relatively small which may limit the generalisability of the findings.

Relationship status was another significant factor. Single and separated adults were the loneliest groups, followed by those in a relationship and divorced, whereas married adults were the least lonely group among all. However, it is important to highlight that the sample was relatively small in separated and divorced groups, possibly affecting the results. Nevertheless, the findings are consistent with previous research suggesting that social support and relationship stability are crucial factors in mitigating feelings of

loneliness (Zhang & Dong, 2022). The higher levels of loneliness reported by single and separated individuals is also supported with previous findings that the lack of close interpersonal connections is strongly linked to increased loneliness levels (Hawkley & Cacioppo, 2010). Moreover, according to "Social Support Theory" (Cohen & Wills, 1985), individuals with limited social networks, such as those who are single or separated, are more vulnerable to loneliness because they lack the buffering effects of emotional support. Interestingly, the intermediate levels of loneliness observed in the divorced and those in a relationship groups suggest that relationship quality may play an important role. Individuals in a relationship, though not married, still have social connections, which might offer some degree of emotional support but may not be as robust or stable as those in a marriage (Kislev, 2022). For divorced individuals, the experience of loneliness may be influenced by relationship dissolution and its aftermath, which can lead to emotional distress and social withdrawal (Haggerty, 2024).

In line with this, living condition showed that participants living alone or in a shared house reported significantly higher loneliness while those living with a partner or spouse reported the lowest levels of loneliness. This supports previous research emphasising the protective effects of cohabiting with a romantic partner, likely due to increased access to emotional intimacy and daily social interaction (Luchetti, 2020; Schafer et al., 2022; Lasgaard et al., 2016).

Employment status also emerged as a significant predictor of loneliness. Homemakers and unemployed adults reported the highest levels of loneliness, and they were followed by part-time employees and students, while adults who are retired were the least lonely group. Although the sample size in the loneliest groups was small, this

pattern may reflect the importance of having structured daily routines and regular social engagement in non-working populations (Durak et al., 2023).

In contrast to these findings, biological sex, education level and ethnicity were not significantly associated with loneliness. This result may be due to sample-specific characteristics, or other factors, such as individual psychological traits or social support, play a more central role in predicting loneliness in this context.

Several limitations in this study should be acknowledged as well. Firstly, although the UCLA Loneliness scale (Version 3; Russell, 1996) is widely used with excellent internal reliability, it does not differentiate emotional, social, existential and collective loneliness which limits the opportunity to explore further, the nuanced type of loneliness associated with different sociodemographic variables. Future research would benefit from using multidimensional loneliness scales. Secondly, the older adult group was relatively small and underrepresented. Given that loneliness in later life is often shaped by distinct factors (e.g., bereavement, health decline, mobility loss; Moeyersons et al., 2022), the older sample in the current study may not adequately reflect the diversity of experiences in this group. Lastly, how these sociodemographic predictors interact with each other was not examined due to uneven subgroup sizes which could prove a more nuanced understanding on how these factors collectively contribute to loneliness. Future research should investigate the interactions between these sociodemographic variables, consider life transitions such as divorce, migration, job or partner loss, and include more diverse psychological predictors such as attachment styles, coping mechanisms, and cultural factors (individualism vs collectivism) to explore the complex nature of loneliness. Additionally, exploring how digital communication and Artificial Intelligence (AI) usage habits (e.g., virtual friendship or

romantic relationship with AI chatbots, interactions with AI robots both as romantic companions and assistive care for older individuals, engagement with social media, online gaming, and online dating apps) interact with loneliness could offer a deeper understanding of loneliness in increasingly digitalised societies.

Despite its limitations, this study has several strengths as well. The current study involved relatively large and diverse sample to explore a comprehensive range of sociodemographic factors. Particularly, findings from relationship status, living condition, and employment status bring relatively a novelty to the study which are less explored predictors of loneliness.

5. Conclusion

This study explored the associations between sociodemographic factors and loneliness in a diverse adult sample and confirmed the role of developmental vulnerabilities contributing to loneliness. While age, relationship status, living condition, and employment status significantly predicted loneliness; biological sex, education, and ethnicity were not significant predictors. These findings provide a foundation for understanding how sociodemographic factors contribute to loneliness and a context to examine more complex psychological models. Addressing both structural and psychological contributors is essential for developing effective psychosocial interventions to mitigate loneliness.

Study 2b

Psychological Predictors of Loneliness: The Role of Depression, Social Anxiety and Alexithymia

1. Introduction

There has been an increased interest to understand the multi-layered mechanisms involved in prolonged loneliness and what psychological, cognitive and social processes might be implicated considering its negative impacts on individuals' well-being. According to literature, beyond sociodemographic predictors, individual differences in cognitive, emotional and social processing have emerged as key predictors of loneliness (Cacioppo & Cacioppo, 2018; Lim et al., 2020). Among these, *depression* is one of the key affective factors which is highly comorbid with loneliness across age groups (Mann et al., 2022). Depression is defined by the APA as *"a mood disorder characterised by persistent feelings of sadness, loss of interest in activities, and difficulties in functioning"* (American Psychiatric Association, 2013, *p.155*). Across longitudinal studies, the relationship between depression and loneliness has been found bidirectional where each can be an antecedent or an outcome (Sbarra et al., 2023; Van As et al., 2022). Loneliness often precedes depression, acting as an emotional stressor that triggers maladaptive cognitive distortions, which can gradually evolve into depressive symptoms (Oltean et al., 2024; Beck & Bredemeier, 2016; Lasgaard et al., 2011). Conversely, depressive symptoms may cause people to withdraw from social interactions, for instance, people with severe depression are likely to remember negative

information and experience social interactions less rewarding (Luo, 2023; Lewis et al., 2017). This cycle is further intensified by *social anxiety*, characterised by a fear of negative evaluation and the tendency to avoid social interactions, which in turn deepens feelings of loneliness (Lim et al., 2016; Moeller & Seehuus, 2019). Social anxiety is also considered to act as both a predictor and a reinforcing feelings of isolation and withdrawal because they share an important common cognitive feature, which is hypervigilance to social threat (Danneel et al., 2019; Hawkley & Cacioppo, 2010). For instance, social anxiety has been linked to altered processing of social stimuli similar to loneliness (Lange et al., 2011; Amir et al., 2011). Hence, depression and social anxiety are two psychopathological symptoms that are closely related to loneliness; moreover, they have been associated with difficulties in facial emotion recognition (Collin et al., 2013; Heuer et al., 2007); cognitive biases (Fodor et al., 2020; Kimbrel et al., 2012); and emotion identification (Liu et al., 2021; Nook et al., 2017).

Building upon this, it is relevant to consider the role of *alexithymia*, defined as the inability to identify, express, or describe one's emotions and others' facial expressions which prevents them from adaptive social interactions in daily life (Di Tella et al., 2020). Alexithymia is a personality construct that is closely intertwined with both depression and social anxiety, because individuals with impaired cognitive emotion processing are more susceptible to developing these conditions (Kajanoja et al., 2017; Wu et al., 2022). Moreover, alexithymia has been associated with loneliness, likely due to challenges in emotional awareness and social connection (Qualter et al., 2009; Wu et al., 2022).

Despite growing recognition of these factors, previous studies did not investigate the dynamic interplay between loneliness, depression, social anxiety and alexithymia, within a unified model. Therefore, to address this gap in the literature, the current study

tested a set of hypotheses examining both mediating and moderating pathways linking, alexithymia, depression, and social anxiety to explore through which the three psychological factors contribute to loneliness.

H1. Higher levels of alexithymia are positively associated with higher levels of loneliness.

H2. Depression mediates the relationship between alexithymia and loneliness.

H3. Social anxiety mediates the relationship between alexithymia and loneliness.

H4. Depression and social anxiety act as independent and parallel mediators in the relationship between alexithymia and loneliness.

H5. Social anxiety moderates the relationship between depression and loneliness.

2. Methods

2.1. Participants

A total of 430 adult participants (M_{age} = 39.47, SD = 19.52, ranged from 18 to 83 years) were recruited for this online study, which was conducted using either Gorilla Experiment Builder (Anwyl-Irvine et al., 2020) or Qualtrics (Qualtrics, Provo, UT). Demographic characteristics of participants and descriptive statistics are presented in Table 6.

2.2. Measures

Demographic variables: All participants completed a series of questionnaires to collect socio-demographic variables on age, biological sex, level of education, living condition relationship status, employment status, and ethnicity.

Table 6. Participant Demographics and Descriptive Statistics (*N* = 430)

Age Mean (+/- SD)	39.47 (19.52)	***Employment***	
Sex		*Student*	119 (27.6%)
Female	287 (66.7%)	*Part-time employed*	82 (19.1%)
Male	143 (33.3%)	*Full-time employed*	87 (20.2%)
Education level		*Self-employed*	40 (9.3%)
Middle school	5 (1.2%)	*Homemaker*	11 (2.6%)
Highschool	238 (55.3%)	*Retired*	72 (16.7%)
Bachelor's degree	129 (30.0%)	*Unemployed*	19 (4.5%)
Master's degree	45 (10.5%)	***Ethnicity***	
PhD	13 (3.0%)	*White*	339 (78.8%)
Living condition		*Black or Black British - African*	36 (8.4%)
Alone	63 (14.7%)	*Asian or Asian British - Indian*	13 (3.0%)
With parents	43 (10.0%)	*Chinese*	15 (3.5.%)
With other family members	27 (6.3%)	*Mixed - White and Asian*	11 (2.6.%)
With friends or shared house	119 (27.7%)	*Mixed - White and Black African*	11 (2.6%)
With partner/husband/wife	178 (41.4%)	*Arab*	5 (1.2%)
Relationship status		***Scales***	
Single	126 (29.3%)	*Loneliness Mean (+/- SD)*	44.93 (11.75)
In a relationship	138 (32.1%)	*Depression Mean (+/- SD)*	10.22 (6.53)
Married	144 (33.5%)	*Social Anxiety Mean (+/- SD)*	8.13 (6.17)
Separated	10 (2.3%)	*Alexithymia Mean (+/- SD)*	28.54 (9.93)
Divorced	12 (2.8%)		

Loneliness: The UCLA Loneliness Scale (Version 3; Russell, 1996) was used to measure participants' level of loneliness. The instrument consists of 20 items (e.g., "How often do you feel left out?"). Responses vary on a scale from 1 (*never*) to 4 (*often*) and are scored continuously as the instrument does not provide validated cut-off points. Total scores range from 20 to 80. Internal consistency in this sample was excellent (α= .94).

Depression: The Center for Epidemiologic Studies Short Depression Scale (Ces-D-R-10; Radloff, 1977), a 10-item scale designed to measure depressive symptomatology was

used. Items are rated on a four-point scale (*from 0=rarely or none of the time to 3=most or all the time*). Total scores range from 0 to 30, with higher scores representing a more depressed mood. Internal consistency in this sample was very good (α= .89).

Social anxiety: Social Interaction Anxiety-6 (SIAS-6; Peters et al., 2012) was used to measure participants' level of social anxiety regarding initiating and maintaining social connections. The items were measured on a 5-point Likert scale (*from 0=Not at all to 5=Extremely*). Total scores range from 0 to 24 with recommended cut-off score 7 or higher (Zsio et al., 2021). Internal consistency in this sample was very good (α= .89).

Alexithymia: The Toronto Alexithymia Scale (TAS; Bagby et al., 1994) was used to measure alexithymia, a 5-point Likert-type measure (from *1=strongly disagree to 5=strongly agree*). The full scale consists of three dimensions: difficulty identifying feelings (DIF; 7 items), difficulty describing feelings (DDF; 5 items), and external-oriented thinking (EOT; 8 items). In the current study only DIF and DDF dimensions were used, hence, producing a total score range of 12 to 36. Internal consistency in this sample was excellent (α= .92).

2.3. Study Design and Analysis

The study employed a cross-sectional correlational design to examine the extent to which psychological factors statistically predicted individual differences in loneliness. Simple mediations were conducted to test whether depression and social anxiety independently or simultaneously mediated the relationship between alexithymia and loneliness. In addition, parallel mediation was used for the assessment of these variables simultaneously. Additionally, a moderation analysis was conducted to test whether social anxiety moderated the relationship between depression and loneliness. The

analyses included bootstrapping with 5000 samples and fully standardised coefficients, and the confidence intervals were computed using the delta method. These analyses were performed using Jamovi (The Jamovi Project, 2024) and RStudio (Posit, PBC, 2024), enabling both basic and advanced statistical techniques.

3. Results

To establish preliminary associations among the core study variables, bivariate Pearson correlations were conducted between loneliness, depression, social anxiety and alexithymia (Table 7). All four constructs, *loneliness, depression, social anxiety* and *alexithymia*, were significantly and positively correlated with one another at the $p < .001$ level, indicating strong evidence for these relationships.

Table 7. Correlation Matrix of Loneliness, Depression, Social Anxiety and Alexithymia

Correlation Matrix

		Loneliness	Depression	Social Anxiety	Alexithymia
Loneliness	**Pearson's r**	—			
	df	—			
	p-value	—			
Depression	**Pearson's r**	0.509***	—		
	df	428	—		
	p-value	<.001	—		
Social Anxiety	**Pearson's r**	0.455***	0.439***	—	
	df	428	428	—	
	p-value	<.001	<.001	—	
Alexithymia	**Pearson's r**	0.523***	0.515***	0.636***	—
	df	428	428	428	—
	p-value	<.001	<.001	<.001	—

Note. * p < .05, ** p < .01, *** p < .001

3.1. Depression as a Mediator Between Alexithymia and Loneliness

A mediation analysis was conducted to examine whether depression mediates the relationship between alexithymia and loneliness. The total effect of alexithymia on loneliness was significant, β = .523, *SE* = .049, *z* = 12.709, *p* < .001, indicating that individuals with higher levels of alexithymia reported higher loneliness (Table 8). The total effect involved both direct and indirect effect through depression. The indirect effect of alexithymia on loneliness through depression was significant, β = .168, *SE* = .032, *z* = 6.228, *p* < .001. This indicates that greater alexithymia predicted increased depression, β = .515, *SE* = .027, *z* = 12.467, *p* < .001, which in turn predicted increased loneliness, β = .326, *SE* = .081, *z* = 7.190, *p* < .001. Importantly, the direct effect of alexithymia on loneliness remained significant after accounting for depression the mediator, β = .355, *SE* = .054, *z* = 7.837, *p* < .001, suggesting partial mediation (Figure 21).

Table 8. Indirect, Direct, and Total Effects of Alexithymia on Loneliness Mediated by Depression

				95% C.I. (a)				
Type	**Path**	**Estimate**	**SE**	**Lower**	**Upper**	**β**	**z**	**p**
Indirect	**Alexithymia ⇒ Depression ⇒ Loneliness**	0.199	0.032	0.133	0.270	0.168	6.228	<.001
Component	**Alexithymia ⇒ Depression**	0.339	0.027	0.282	0.390	0.515	12.467	<.001
	Depression ⇒ Loneliness	0.586	0.081	0.407	0.768	0.326	7.190	<.001
Direct	**Alexithymia ⇒ Loneliness**	0.420	0.054	0.310	0.536	0.355	7.837	<.001
Total	**Alexithymia ⇒ Loneliness**	0.619	0.049	0.527	0.710	0.523	12.709	<.001

Note. Confidence intervals computed with method: Bootstrap percentiles

Note. Betas are completely standardized effect sizes

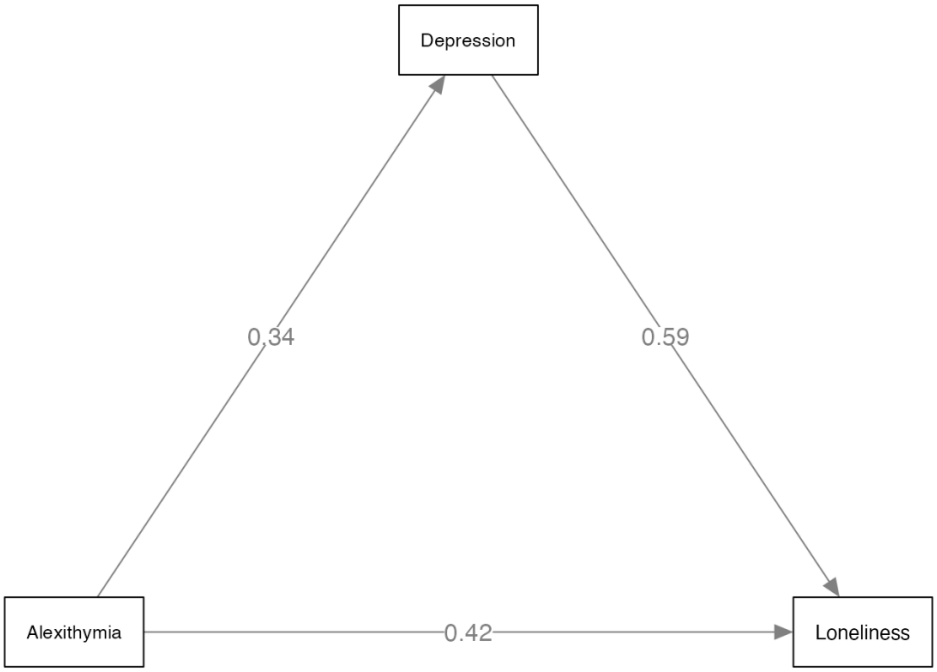


Figure 21. Standardised Path Model Showing the Mediating Role of Depression in the Relationship Between Alexithymia and Loneliness

3.2. Social Anxiety as a Mediator Between Alexithymia and Loneliness

Another mediation analysis was conducted to examine whether social anxiety mediates the relationship between alexithymia and loneliness. As shown in Table 9 and Figure 22, the total effect of alexithymia on loneliness comprised both direct effect and indirect effect through social anxiety. The indirect effect of alexithymia on loneliness through social anxiety was significant, β = .131, *SE* = .040, *z* = 3.828, *p* < .001. Similar to the influence of depression on loneliness, higher alexithymia predicted increased social anxiety, β = .636, *SE* = .023, *z* = 17.100, *p* < .001, which in turn predicted increased loneliness, β = .206, *SE* = .100, *z* = 3.928, *p* < .001. Importantly, the direct effect of alexithymia on loneliness remained significant after accounting for social anxiety the mediator, β = .392, *SE* = .062, *z* = 7.492, *p* < .001, suggesting partial mediation.

Table 9. Indirect, Direct, and Total Effects of Alexithymia on Loneliness

				95% C.I. (a)				
Type	**Path**	**Estimate**	**SE**	**Lower**	**Upper**	**β**	**z**	**p**
Indirect	**Alexithymia ⇒ Social anxiety ⇒ Loneliness**	0.155	0.040	0.076	0.234	0.131	3.828	<.001
Component	**Alexithymia ⇒ Social anxiety**	0.395	0.023	0.350	0.441	0.636	17.100	<.001
	Social anxiety ⇒ Loneliness	0.392	0.100	0.196	0.587	0.206	3.928	<.001
Direct	**Alexithymia ⇒ Loneliness**	0.464	0.062	0.343	0.586	0.392	7.492	<.001
Total	**Alexithymia ⇒ Loneliness**	0.619	0.049	0.524	0.715	0.523	12.709	<.001

Note. Confidence intervals computed with method: Standard (Delta method)

Note. Betas are completely standardized effect sizes

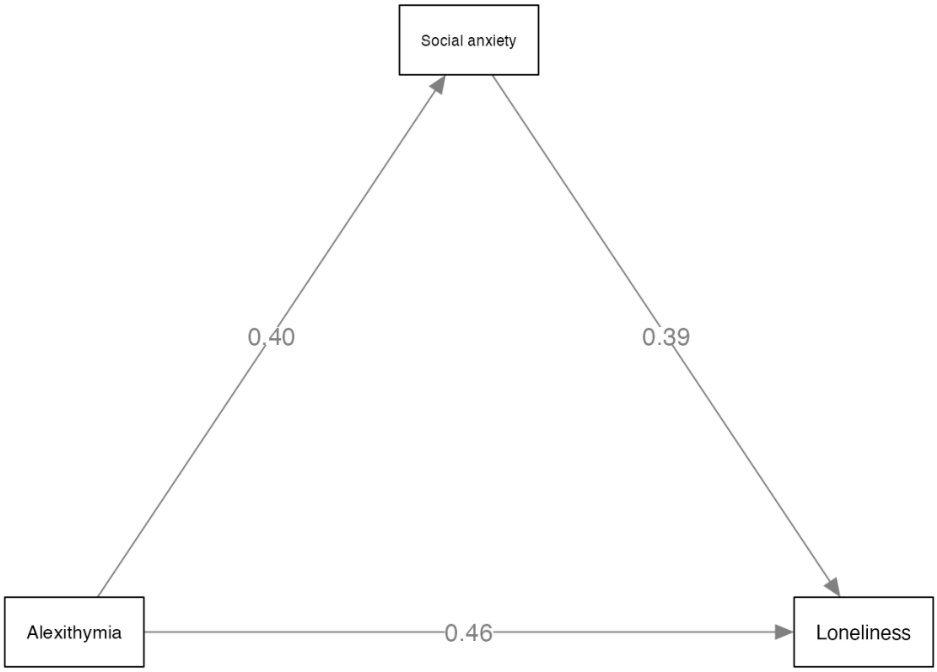


Figure 22. Standardized Path Model Showing the Mediating Role of Social Anxiety in the Relationship Between Alexithymia and Loneliness

3.3. Parallel Mediation of Social Anxiety and Depression in Alexithymia-Loneliness Association

After observing the partial mediation effects of depression and social anxiety between alexithymia and loneliness, further investigation was conducted with a parallel mediation analysis to examine whether depression and social anxiety independently mediate the relationship between alexithymia and loneliness.

As shown in Table 10 and Figure 23, the total effect of alexithymia on loneliness was significant, $\beta = .526$, $SE = .048$, $z = 12.889$, $p < .001$, indicating that higher alexithymia is associated with higher loneliness. The total indirect effect through both depression and social anxiety was also significant, $\beta = .252$, $SE = .046$, $z = 6.488$, $p < .001$. This effect included two significant, independent indirect pathways. The indirect effect through depression ($a1 \times b1$) was $\beta = .157$, $SE = .035$, $z = 5.350$, $p < .001$. The indirect effect through social anxiety ($a2 \times b2$) was $\beta = .095$, $SE = .038$, $z = 2.936$, $p < .001$. The direct effect of alexithymia on loneliness, controlling for both mediators, remained significant, $\beta = .273$, $SE = .068$, $z = 4.764$, $p < .001$, suggesting partial mediation.

Together, these findings support a model in which both depression and social anxiety mediate the relationship between alexithymia and loneliness, with depression having a slightly stronger mediating effect.

Table 10. Parallel Mediation of Depression and Social Anxiety in the Relationship Between Alexithymia and Loneliness

				95% C.I. (a)				
Type	**Path**	**Estimate**	**SE**	**Lower**	**Upper**	**β**	**z**	**p**
Indirect	**Alexithymia ⇒ Depression ⇒ Loneliness (a1 x b1)**	0.185	0.035	0.119	0.257	0.157	5.350	<.001
	Alexithymia ⇒ Social anxiety ⇒ Loneliness (a2 x b2)	0.112	0.038	0.040	0.189	0.095	2.936	<.001
Component	**Alexithymia ⇒ Depression (a1)**	0.339	0.028	0.282	0.391	0.515	12.321	<.001
	Alexithymia ⇒ Social anxiety (a2)	0.395	0.024	0.347	0.443	0.636	16.225	<.001
	Depression ⇒ Loneliness (b1)	0.545	0.092	0.364	0.729	0.305	5.909	<.001
	Social anxiety ⇒ Loneliness (b2)	0.284	0.095	0.102	0.472	0.150	2.984	=.003
Direct	**Alexithymia ⇒ Loneliness (c')**	0.322	0.068	0.185	0.454	0.273	4.764	<.001
Total Indirect	**ab1 + ab2**	0.297	0.046	0.212	0.390	0.252	6.488	<.001
Total Effect	**c = ab1 + ab2 + c'**	0.619	0.048	0.525	0.714	0.526	12.889	<.001

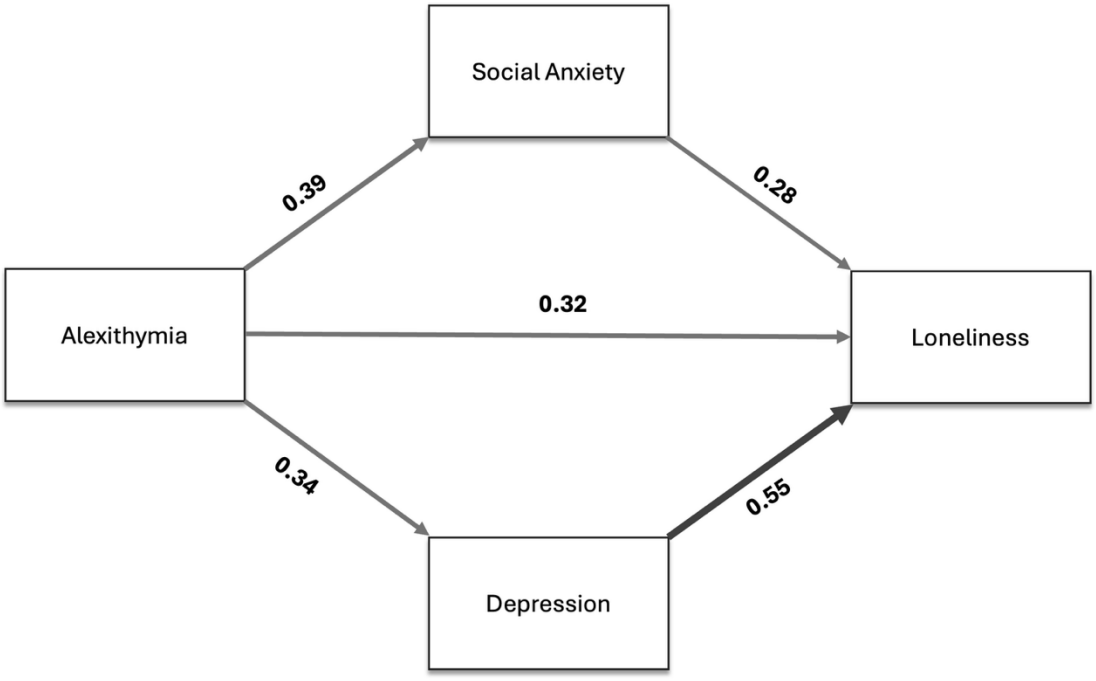


Figure 23. Parallel Mediation Model of Depression and Social Anxiety in the Relationship Between Alexithymia and Loneliness

3.4. Social Anxiety as a Moderator of the Depression–Loneliness Association

After observing both independent and parallel mediation of depression and social anxiety on the relationship between alexithymia and loneliness, further investigation was conducted with moderation analysis to examine whether the association between depression and loneliness was moderated by social anxiety. Depression and social anxiety were considered as predictors, along with their interaction term (Depression × Social Anxiety), with loneliness as the outcome variable.

As shown in Table 11, both depression (β = .490, *SE* = .120, *z* = 7.333, *p* < .001) and social anxiety (β = .438, *SE* = .145, *z* = 5.757, *p* < .001) were significant positive predictors of loneliness. Importantly, the interaction between depression and social anxiety was also significant, β = −.238, *SE* = .010, *z* = 2.555, *p* = .011, indicating a moderation effect.

The interaction was probed using simple slopes analysis and is illustrated in Figure 24. The results showed that the positive association between depression and loneliness was stronger at higher levels of social anxiety (+1 SD) and weaker at lower levels of social anxiety (–1 SD). This indicates a moderation effect, where social anxiety amplifies the association between depression and loneliness. In other words, individuals with higher social anxiety may be more vulnerable to experiencing loneliness in the context of depressive symptoms, whereas those with lower social anxiety may be less affected by depressive symptoms in this regard. While social anxiety functioned as a mediator in previous models, its role in this analysis is conceptually distinct; here, it operates as a moderator, influencing the *magnitude* of the association between depression and loneliness rather than serving as a pathway through which this relationship occurs.

Table 11. Moderation Analysis of the Interaction Between Depression and Social Anxiety on Loneliness

			95% C.I. (a)				
Path	**Estimate**	**SE**	**Lower**	**Upper**	**β**	**z**	**P**
Depression ⇒ Loneliness	0.881	0.120	0.640	1.113	0.490	7.333	<.001
Social anxiety ⇒ Loneliness	0.834	0.145	0.544	1.116	0.438	5.757	<.001
Depression * Social anxiety ⇒ Loneliness	-0.025	0.010	-0.043	-0.005	-0.238	-2.55	=.011

Note. Confidence intervals computed with method: Standard (Delta method)

Note. Betas are completely standardized effect sizes

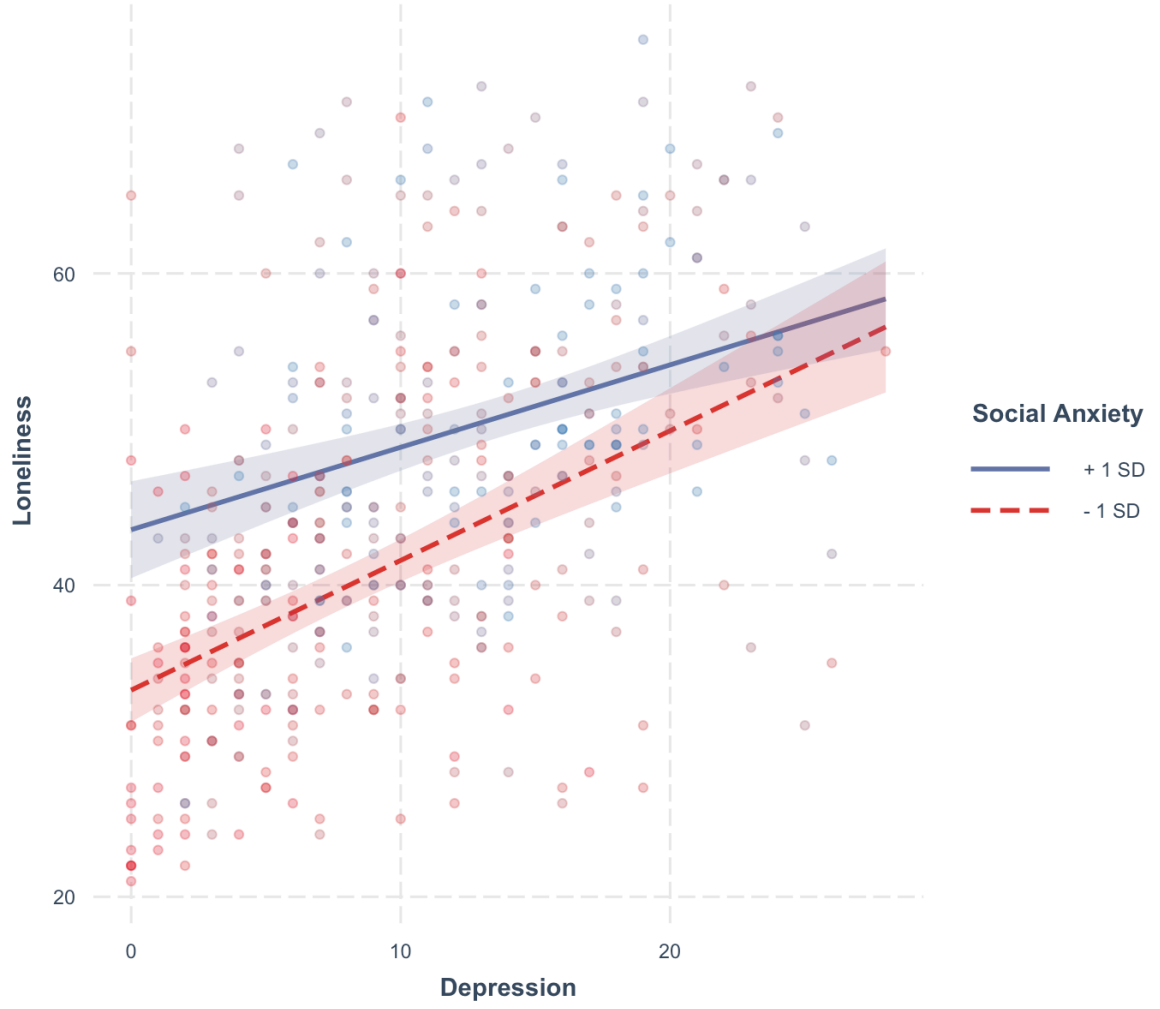


Figure 24. Social Anxiety as a Moderator of the Depression and Loneliness Association

Note. Simple slopes are plotted at ±1 SD of social anxiety. The relationship between depression and loneliness is stronger at higher levels of social anxiety.

4. Discussion

The current study aimed to explore the psychological mechanisms underlying loneliness, particularly the roles of depression, social anxiety and alexithymia. The results revealed three main findings. Firstly, depression and social anxiety independently mediated the relationship between alexithymia and loneliness, with depression having a stronger effect. Secondly, alexithymia had both significant direct and indirect effects on loneliness which provided insights into how difficulties in processing of ones' emotions contributes to loneliness beyond depression and social anxiety symptoms. Lastly, social anxiety moderated the relationship between depression and loneliness, which suggest that individuals with higher social anxiety experience higher loneliness when being depressed than those with low social anxiety.

Consistent with previous research (Zhang et al., 2023; Qualter et al., 2009), alexithymia was strongly associated with loneliness. Higher alexithymia was linked to higher levels of depression and social anxiety, which in turn, associated with increased level of loneliness. This pattern supports the theory that individuals with alexithymia are not only prone to having difficulties in recognising, identifying, and describing emotions which impairs social interactions (Kajanoja et al., 2017; Wu et al., 2022), but also demonstrate heightened vulnerability to depression and social anxiety which intensify their feelings of loneliness (Radetzki et al., 2021; Ertekin et al., 2015). Furthermore, the direct effect of alexithymia on loneliness remained significant even after controlling for depression and social anxiety, suggesting that emotional processing deficits independently contribute to loneliness beyond these psychological factors.

This points to a unique role of emotion processing difficulties which is aligned with what has been discussed regarding interpretation bias in loneliness in the Scoping

Review in Chapter 2. Individuals who have difficulties in accurately decoding others' emotions, for instance misinterpreting neutral facial expressions as negative, may disruption in interpersonal communication and understanding, hence reducing social opportunities for connection. This disruption is especially significant considering the conflicted approach-avoidance motivations that lonely individuals experience, as documented in the limited existing literature. Individuals high in alexithymia may struggle to regulate social behaviours in context-sensitive ways, leading to rigid avoidance responses even when social cues are positive. This misattunement might also compromise emotional contagion. According to the "Theory of Primitive Emotional Contagion" (Hatfield et al., 1994, *p.153*), *"emotional contagion is the tendency to automatically mimic and synchronize expressions, vocalisations, postures and movements with those of another person and, consequently, to converge emotionally"*. The emotional contagion consists of the following courses: (1) emotional awareness (e.g., decoding nonverbal cues, such as facial expressions, tone of voice, and body movements); (2) unconscious mimicry (e.g., subtle facial emotion mirroring); (3) physiological feedback (e.g., embodiment of emotions); and (4) emotional resonance (Zhang et al., 2016). Consequently, alexithymia may reduce the likelihood of this shared affective resonance and prevent formation of interpersonal connection reinforcing the feelings of loneliness even in the presence of others.

Apart from this, the results from mediation analyses on depression and social anxiety also align with the previous literature suggesting that depression and social anxiety are both significant predictors of loneliness (Cacioppo & Cacioppo, 2018; Lim et al., 2020). Specifically, depression may intensify loneliness by reducing motivation to socially engage with others, amplifying negative self-perceptions and contributing to

cognitive distortions through rumination (Şimşek & Koydemir, 2013; Simsek & Zincir, 2024). Meanwhile, social anxiety might exacerbate loneliness by fostering social avoidance because of fear of negative evaluation (Moeller & Seehuus, 2019).

Furthermore, as evident in moderation analysis, social anxiety amplifies the influence of depression on loneliness. Specifically, the relationship between depression and loneliness was stronger at higher levels of social anxiety, indicating that individuals with high social anxiety are more likely to experience increased loneliness in response to depressive symptoms. This finding supports the idea that social anxiety worsens the emotional impact of depression possibly because of heightened social threat sensitivity explained in the evolutionary theory of loneliness (Cacioppo & Hawkley, 2009).

Overall, the interplay between these psychological factors and loneliness underscores that loneliness is not merely a consequence of a single factor but rather the culmination of multiple interconnected psychological vulnerabilities. Hence, this study extends previous research by demonstrating that alexithymia contributes to loneliness through multiple pathways both directly and indirectly via depression and social anxiety. This study is also the first study in the literature, to our knowledge, to examine the dynamic interplay between loneliness, depression, social anxiety and alexithymia, within a unified model, offering novel insights into their interrelated roles in the development and maintenance of loneliness.

The current study has some limitations as well. For instance, cross-sectional design limits casual inferences, therefore longitudinal studies are needed to confirm mediation. Also, age and sex variability was not examined; future studies could examine whether these psychological mechanism vary across sociodemographic factors. Despite limitations, this study also provide insights into how psychological interventions should

be designed for loneliness. For instance, interventions could target emotion identification, particularly for individuals with alexithymia and tailored interventions could be beneficial for individuals to benefit from behavioural activation particularly for lonely individuals with high social anxiety. Cognitive-behavioural interventions, which have been shown to effectively reduce both depression and social anxiety (Hofmann et al., 2012; Cuijpers et al., 2014), may be particularly beneficial for individuals struggling with emotional awareness and regulation. Overall, the complex relationships found in this study between these psychological factors and loneliness provide implications for both theoretical framework and practical understanding for researchers and clinicians.

5. Conclusion

This study provides valuable insights into the psychological predictors of loneliness, emphasising the complex roles of depression, social anxiety and alexithymia. Particularly, this study highlights the significant role of emotional processing as a core driver in understanding loneliness. The findings revealed that alexithymia contributes to loneliness both directly and indirectly, while its effects are also mediated by depression and social anxiety. Therefore, the psychological interventions should be tailored to effectively tackle loneliness by focusing on these key psychological vulnerabilities.

Study 2c

Behavioural and Social Predictors of Loneliness: The Role of Depression, Avoidance and Trust

1. Introduction

While loneliness is often understood as a subjective emotional experience, it emerges from a complex interplay of behavioural, psychological, and interpersonal factors. Among these, patterns of avoidance and interpersonal trust have received growing attention in recent years (Zhang et al., 2024; Bellucci et al., 2025; Chen et al., 2025). Yet, the role of underlying affective states, particularly depression, in shaping these dynamics remains underexplored.

Depression has long been associated with increased feelings of loneliness, often acting as both a precursor and a consequence in a cyclical relationship (Sbarra et al., 2023; Kraav et al., 2021). Individuals with higher levels of depression tend to withdraw from social interactions, experience reduced motivation for social relationships and demonstrate heightened sensitivity to rejection which can intensify loneliness (Ottenbreit & Dobson, 2004; van Winkel et al., 2017; Watson et al., 2012).

This cyclical relationship between depression and loneliness may be maintained through some factors that shape individuals' engagement in social contexts, particularly behavioural motivations. For instance, when depressive symptoms reduce motivations for social engagements and increase avoidance, they also limit their opportunities to form meaningful and social connections (Yuan et al., 2022). According to the "Social

Motivation Theory" (Asendorpf, 1990), social withdrawal occurs when social avoidance motivation, which is driven by fear of rejection, overrides social approach motivation. Research on social avoidance is relatively new, and underlying reasons are still controversial. However, there are accumulative research in the literature suggesting that depression, social anxiety, behavioural inhibition, and fear of negative evaluation seem to aggravate social avoidance (Yuan et al., 2022; Weeks et al., 2008). For instance, in an experimental study, Weerdmeester and Lange (2019) found that while individuals with low social anxiety demonstrated response to rejection with a compensatory approach tendencies, individuals with higher level of social anxiety instead showed greater avoidance behaviours.

While loneliness has not been investigated enough in terms of approach-avoidance behaviours, one of the earliest studies exploring the role of avoidance was conducted by Nurmi et al. (1996) using longitudinal survey among young adults. They found that avoidance strategies were associated with higher levels of loneliness while approach-oriented strategies were linked to lower level of loneliness and more adaptive social functioning. Their findings are crucial in understanding the development of loneliness over time due to cognitive and behavioural motivations (approach vs avoidance). Moreover, as evident from Chapter 2, recent findings suggested increased social avoidance motivation among lonely individuals (Skoko et al., 2024; Saporta et al., 2021). For instance, Skoko et al. (2024) found that lonely individuals are more likely to engage in socially avoidant behaviours due to fear of rejection or negative outcome expectations. This finding is in line with studies showing that lonely individuals avoid social interactions (Watson & Nesdale, 2012; Coplan et al., 2013). Ypsilanti et al. (2019) also found that lonely individuals reported greater self-disgust alongside increased self-

and social avoidance. These avoidance tendencies are theoretically linked to difficulties forming positive relationships (Gable et al., 2013).

Although research on this phenomena is limited, previous studies have also identified a clear inverse correlation between loneliness and generalised trust. *Trust,* which is central in social relationships, enables people to have a more accurate assessment of other people's intentions (Grimen, 2009). For instance, Rotenberg (1994) found a negative correlation between loneliness and generalised trust beliefs where lonely adolescents demonstrated less trusting behaviours in the Prisoner's Dilemma Game. Their findings were supported by another study where they reported that loneliness is negatively correlated with trust among peers during adolescence (Rotenberg et al., 2004). Similarly, Qualter et al. (2009) also found that interpersonal distrust had a strong and direct effect on social loneliness. However, some contrary results exist. For instance, Berlingieri et al. (2025) conducted a large-scale trust game experiment where they examined how loneliness affects individuals' behaviours in trust-based situations and found that loneliness leads to higher level of trust. Bellucci et al. (2024) supported these findings where they used economic games and Bayesian predictive models in which participants completed a sequential social decision-making task that assessed how they formed trustworthiness impressions based on others' honest or dishonest behaviours. They found that lonelier individuals trusted their partners more despite expecting them to be less trustworthy, showing a gap between their trust and expectations. In contrast, extraverted and less lonely individuals showed the opposite pattern. The authors argue that, in line with the Evolutionary Theory of Loneliness (Cacioppo et al., 2010), loneliness might act as a warning signal to motivate

lonely individuals to connect with others, hence the findings on higher levels of trust in lonely individuals might originate from this attempt to increase social inclusion.

Ultimately, as of now, there is no research on how these behavioural and social factors interact and amplify each other, even though there is accumulative evidence suggesting that depression is often linked to increased feelings of loneliness and leads to social withdrawal (Yuan et al., 2022; van Winkel et al., 2017; Watson et al., 2012). Therefore, this study aims to address this gap by examining how these factors influence each other, particularly, the mediating role of avoidance and moderating effect of trust between loneliness and depression.

Based on the existing literature and theoretical frameworks, the following hypotheses were formulated to guide the analyses in this study:

H1. Avoidance mediates the relationship between depression and loneliness.
H2. The subtypes of avoidance, cognitive and behavioural, differentially mediate the relationship between depression and loneliness.
H3. Trust moderates the indirect effect of depression on loneliness via avoidance, such that the association between avoidance and loneliness is influenced by the level of trust.

2. Methods

2.1. Participants

A new sample of participants was recruited for Study 2c, distinct from the samples used in previous studies reported in this chapter. A total of 170 participants were included in the study (M_{age} = 32.35, SD = 11.60, age range = 18–74). Demographic characteristics of participants and descriptive statistics are presented in Table 12.

Table 12. Participant Demographics and Descriptive Statistics (*N* = 170)

Age Mean (+/- SD)	32.35 (11.60)
Sex	
Female	129 (75.8%)
Male	41 (24.2%)
Education level	
Middle school	2 (1.2%)
Highschool	58 (34.1%)
Bachelor's degree	31 (18.2%)
Master's degree	59 (34.7%)
PhD	20 (11.8%)
Living condition	
Alone	34 (10.0%)
With parents	23 (13.5%)
With other family members	12 (7.1%)
With friends or shared house	49 (28.9%)
With partner/husband/wife	52 (30.6)
Relationship status	
Single	77 (45.3%)
In a relationship	47 (27.6%)
Married	37 (21.9%)
Separated	3 (1.4%)
Divorced	6 (3.5%)
Employment	
Student	67 (39.4%)
Part-time employed	28 (16.4%)
Full-time employed	45 (26.4%)
Self-employed	14 (8.2%)
Homemaker	3 (1.7%)
Retired	3 (1.7%)
Unemployed	10 (5.9%)
Ethnicity	
White	118 (69.4%)
Black or Black British - African	9 (5.3%)
Asian or Asian British - Indian	17 (10.0%)
Chinese	7 (4.1%)
Mixed - White and Asian	10 (5.9%)
Mixed- White and Black African	6 (3.5%)
Arab	3 (1.8%)
Scales	
Loneliness Mean (+/- SD)	45.68 (11.42)
Depression Mean (+/- SD)	13.40 (4.33)
Avoidance Mean (+/- SD)	68.65 (24.27)
Trust Mean (+/- SD)	3.46 (0.72)

2.2. Measures

Demographic variables: Participants completed a questionnaire to collect socio-demographic variables on age, biological sex, education, living condition, relationship status, employment status, and ethnicity.

Loneliness: The UCLA Loneliness Scale (Version 3; Russell, 1996) was used to measure participants' level of loneliness. The instrument consists of 20 items (e.g., "*How often do you feel left out?*"). Responses vary on a scale from 1 (*never*) to 4 (*often*) and are scored continuously as the instrument does not provide validated cut-off points. Total scores range from 20 to 80. Internal consistency in this sample was excellent (α= .96).

Depression: The Center for Epidemiologic Studies Short Depression Scale (Ces-D-R-10; Radloff, 1977), a 10-item measure was used to assess depressive symptomology. Items are rated on a four-point scale (*from 0=rarely or none of the time to 3=most or all the time*). Total scores range from 0 to 30, with higher scores representing a more depressed mood. Internal consistency in this sample was very good (α= .88).

Trust: The 6-item General Trust Scale (GTS; Yamagishi & Yamagishi, 1994) was used in which participants rated on a 5-point scale ranging from 1 (*Strongly disagree*) to 5 (*Strongly agree*) in terms of beliefs about honesty and trustworthiness of others. The score for each item was averaged together to form a continuous measure ranging from 1 to 5. Internal consistency in this sample was excellent (α= .92).

Avoidance: Cognitive Behavior Avoidance Scale (CBAS; Ottenbreit & Dobson, 2004) is a 31-item multi-dimensional measure of avoidance with four factors including *behavioural social and non-social, cognitive social and non-social avoidance*. Respondents indicated how true the mentioned strategies for them using a 5-point scale (*1= not at all true for me to 5= extremely true for me).* The items are summarised to provide an overall score

that ranges from 31 to 155 with a score of 53 is suggested as the optimum cut-off point (Barajas et al., 2017). Higher scores indicate more avoidance. Internal consistency in this sample was excellent (α= .96)[3].

2.3. Study Design and Analysis

This study employed a cross-sectional design. The data was collected on online platforms, Gorilla and Qualtrics, and analysed using Jamovi and RStudio. The primary objective was to explore how avoidance act as mediators in the relationship between depression and loneliness, and whether the influence of avoidance on loneliness was moderated by trust. Simple and parallel mediation models were conducted to examine the mediating role of avoidance, alongside a moderation analysis testing trust as a potential moderator in depression-loneliness link. All models were estimated using bootstrapping with 5000 samples and fully standardised coefficients, with confidence intervals computed using the delta method.

3. Results

Pearson correlation analyses were conducted to examine the relationships between loneliness, depression, avoidance subtypes (behavioural social and non-social, cognitive social and non-social), and trust (Table 13). Loneliness demonstrated strong positive correlations with depression and all avoidance dimensions (all $p < .001$). As expected, trust was negatively correlated with loneliness ($r = -.309$, $p < .001$). Depression showed moderate positive correlations with all four avoidance subtypes, ranging from $r = .386$

[3] *To create composite scores for Cognitive Avoidance and Behavioral Avoidance, the means of their respective social and non-social subscales were calculated to ensure equal weighting regardless of subscale item count and to maintain a consistent scale range across variables. For the total Avoidance score used in the initial mediation model, subscale scores were summed to reflect the overall level of avoidance behaviours.*

to r = .542 (all p < .001), but was not significantly correlated with trust (r = –.050, p = .517). Intercorrelations among the avoidance subtypes were high, particularly between cognitive non-social and cognitive social avoidance (r = .756, p < .001), and between behavioural social and behavioural non-social avoidance (r = .745, p < .001). Trust was not significantly associated with depression or avoidance subtypes (rs ≤ .08, ps ≥ .28) but was negatively correlated with loneliness (r = –.31, p < .001).

Table 13. Correlation Matrix of Loneliness, Depression, Avoidance Subtypes, and Trust

Correlation Matrix

		Loneliness	Depression	BSA	BNSA	CSA	CNSA	Trust
Loneliness	**Pearson's r**	—						
	df	—						
	p-value	—						
Depression	**Pearson's r**	0.588	—					
	df	168	—					
	p-value	<.001	—					
BSA	**Pearson's r**	0.546	0.386	—				
	df	168	168	—				
	p-value	<.001	<.001	—				
BNSA	**Pearson's r**	0.449	0.511	0.745	—			
	df	168	168	168	—			
	p-value	<.001	<.001	<.001	—			
CSA	**Pearson's r**	0.483	0.417	0.676	0.711	—		
	df	168	168	168	168	—		
	p-value	<.001	<.001	<.001	<.001	—		
CNSA	**Pearson's r**	0.489	0.542	0.617	0.711	0.756	—	
	df	168	168	168	168	168	—	
	p-value	<.001	<.001	<.001	<.001	<.001	—	
Trust	**Pearson's r**	-0.309	-0.050	0.002	0.083	0.044	-0.009	—
	df	168	168	168	168	168	168	—
	p-value	<.001	0.517	0.978	0.281	0.574	0.910	—

Note. BSA = Behavioural Social Avoidance; BNSA = Behavioural Non-social Avoidance; CSA = Cognitive Social Avoidance; CNSA = Cognitive Non-social Avoidance.

3.1. Avoidance as a Mediator Between Depression and Loneliness

A mediation analysis was conducted to examine whether avoidance mediates the relationship between depression and loneliness. As shown in Table 14 and Figure 25, the total effect of depression on loneliness was significant, β = .588, *SE* = .164, *z* = 9.419, *p* < .001, indicating that higher levels of depression were associated with higher loneliness. The indirect effect of depression on loneliness via avoidance was significant, β = .187, *SE* = .113, *z* = 4.344, *p* < .001. Specifically, greater depression predicted greater avoidance (β = .533, *SE* = .364, *z* = 8.199, *p* < .001), which in turn predicted greater loneliness, β = .351, *SE* = .032, *z* = 5.123, *p* < .001. The direct effect of depression on loneliness remained significant after accounting for avoidance, β = .401, *SE* = .180, *z* = 5.855, *p* < .001, indicating partial mediation. This might suggest that individuals with higher depressive symptoms are more likely to engage in avoidance, which in turn predicts higher levels of loneliness.

Table 14. Indirect, Direct, and Total Effects of Depression on Loneliness Mediated by Cognitive-Behavioural Avoidance

				95% C.I. (a)				
Type	**Path**	**Estimate**	**SE**	**Lower**	**Upper**	**β**	**z**	**p**
Indirect	**Depression ⇒ Avoidance ⇒ Loneliness**	0.492	0.113	0.279	0.719	0.187	4.344	<.001
Component	**Depression ⇒ Avoidance**	2.984	0.364	2.305	3.672	0.533	8.199	<.001
	Avoidance ⇒ Loneliness	0.165	0.032	0.098	0.229	0.351	5.123	<.001
Direct	**Depression ⇒ Loneliness**	1.055	0.180	0.702	1.443	0.401	5.855	<.001
Total	**Depression ⇒ Loneliness**	1.547	0.164	1.222	1.884	0.588	9.419	<.001

Note. Confidence intervals computed with method: Bootstrap percentiles

Note. Betas are completely standardized effect sizes

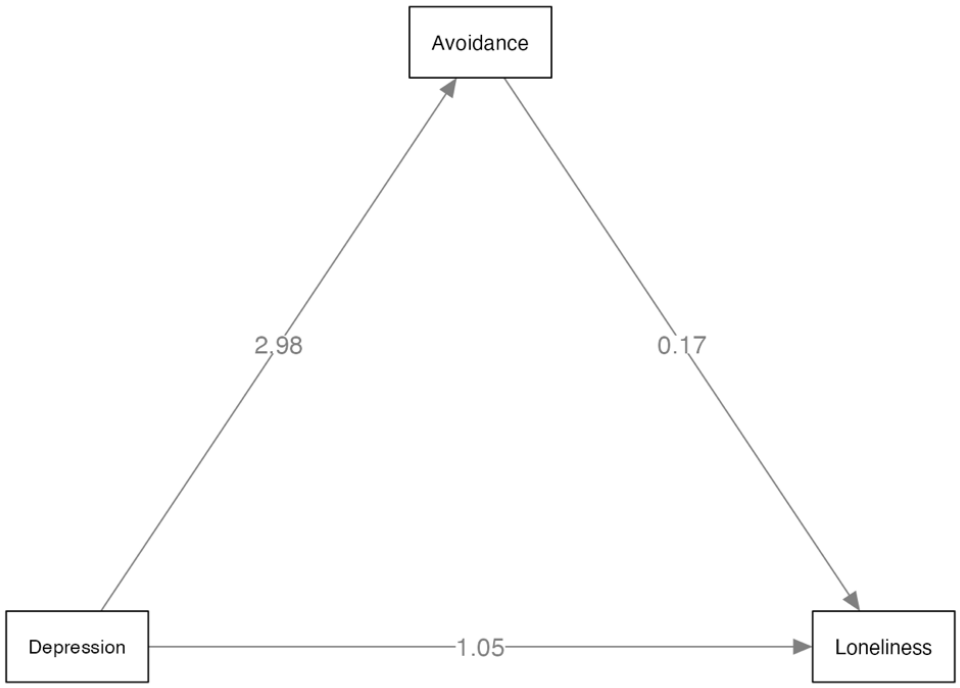


Figure 25. Mediation Model of Depression, Cognitive-Behavioural Avoidance, and Loneliness

Note. The values represent the standardised path coefficients for the mediation model.

3.2. Parallel Mediation of Cognitive and Behavioural Avoidance in Depression-Loneliness Association

A parallel mediation model examined whether cognitive and behavioural avoidance subtypes mediated the relationship between depression and loneliness differently. The total effect of depression on loneliness was significant, β = .588, *SE* = 0.164, *z* = 9.419, *p* < .001. The direct effect of depression on loneliness also remained significant, β = .465, *SE* = .178, *z* = 6.893, *p* < .001, suggesting only partial mediation.

The total indirect effect comprised four specific indirect paths (Table 15). Behavioural social avoidance significantly mediated the relationship between depression and loneliness (β = .161, *SE* = .118, *z* = 3.593, *p* < .001). Behavioural non-social avoidance also showed a significant indirect effect but in a negative direction (β = −.113, *SE* = .138, *z* = −2.157, *p* = .031), indicating that greater behavioural non-social avoidance was associated

with lower loneliness when depression was high. Indirect effects through cognitive social and cognitive non-social avoidance were not significant (both $p > .14$).

All paths from depression to the four avoidance subtypes were statistically significant (*all* $p < .001$), with the strongest association found between depression and cognitive non-social avoidance (β = .542). In contrast, when examining the concurrent associations with loneliness, only two avoidance subtypes showed significant relationships: behavioural social avoidance was positively associated with loneliness (β = .418, $p < .001$), whereas behavioural non-social avoidance showed a small negative association (β = −.221, $p = .025$). Neither cognitive avoidance subtype was significantly linked to loneliness. The direct effect of depression on loneliness remained significant after accounting for mediators (β = .465, $p < .001$), indicating partial mediation (Figure 26).

Table 15. Indirect, Direct, and Total Effects of Depression on Loneliness Mediated by Cognitive and Behavioural Avoidance

				95% C.I. (a)				
Type	**Path**	**Estimate**	**SE**	**Lower**	**Upper**	**β**	**z**	**p**
Indirect	**Depression ⇒ Behavioural Social Avoidance ⇒ Loneliness**	0.424	0.118	0.203	0.663	0.161	3.593	<.001
	Depression ⇒ Behavioural Non-social Avoidance ⇒ Loneliness	-0.297	0.138	-0.591	-0.028	-0.113	-2.157	0.031
	Depression ⇒ Cognitive Social Avoidance ⇒ Loneliness	0.156	0.107	-0.054	0.425	0.059	1.463	0.143
	Depression ⇒ Cognitive Non-social Avoidance ⇒ Loneliness	0.041	0.136	-0.264	0.321	0.015	0.298	0.766
Component	**Depression ⇒ Behavioural Social Avoidance**	0.700	0.129	0.461	0.965	0.386	5.434	<.001
	Behavioural Social Avoidance ⇒ Loneliness	0.606	0.126	0.317	0.854	0.418	4.790	<.001

				95% C.I. (a)				
Type	**Path**	**Estimate**	**SE**	**Lower**	**Upper**	**β**	**z**	**p**
	Depression ⇒ Behavioural Non-social Avoidance	0.543	0.070	0.388	0.686	0.511	7.727	<.001
	Behavioural Non-social Avoidance ⇒ Loneliness	-0.548	0.244	-1.057	-0.063	-0.221	-2.246	0.025
	Depression ⇒ Cognitive Social Avoidance	0.459	0.077	0.323	0.612	0.417	5.956	<.001
	Cognitive Social Avoidance ⇒ Loneliness	0.340	0.225	-0.113	0.880	0.143	1.509	0.131
	Depression ⇒ Cognitive Non-social Avoidance	1.281	0.153	0.955	1.599	0.542	8.387	<.001
	Cognitive Non-social Avoidance ⇒ Loneliness	0.032	0.106	-0.196	0.245	0.028	0.298	0.765
Direct	**Depression ⇒ Loneliness**	1.224	0.178	0.880	1.620	0.465	6.893	<.001
Total	**Depression ⇒ Loneliness**	1.547	0.164	1.243	1.886	0.588	9.419	<.001

Note. Confidence intervals computed with method: Bootstrap percentiles

Note. Betas are completely standardized effect sizes

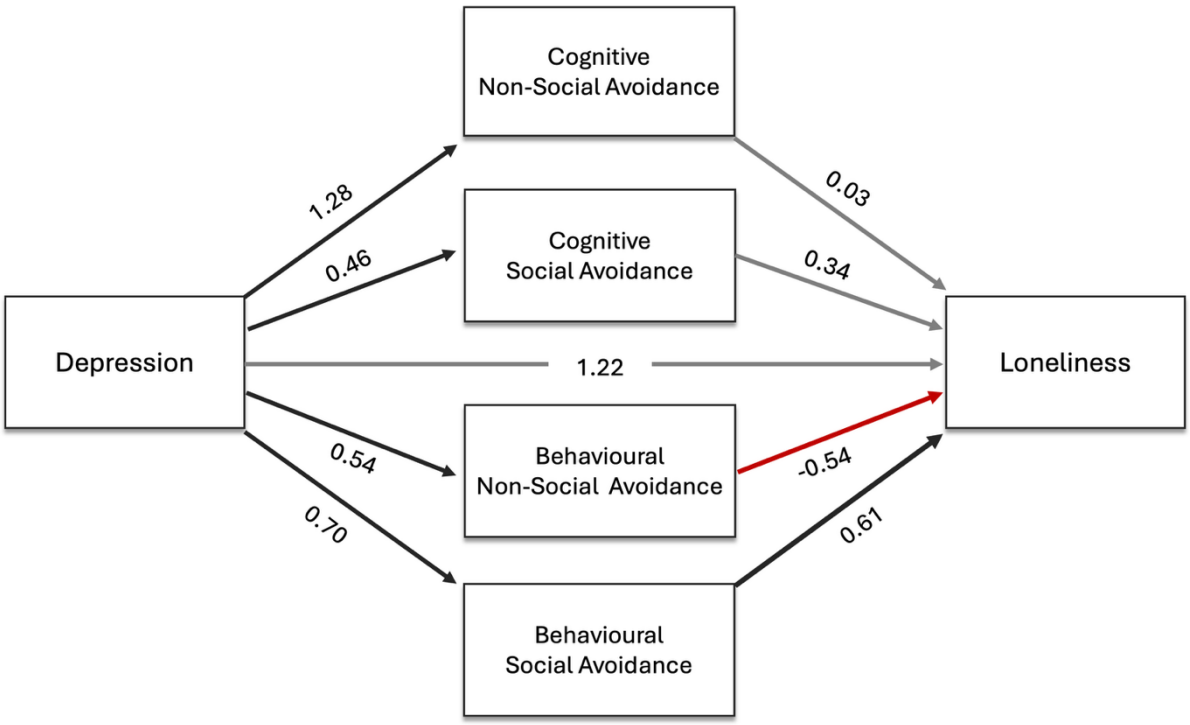


Figure 26.Parallel Mediation Model of Depression, Cognitive and Behavioural Avoidance (both social and non-social) and Loneliness

3.3. Serial Mediation of Depression on Loneliness via Cognitive and Behavioural Avoidance

Following the parallel mediation model, a serial mediation analysis was tested to examine whether the statistical associations among depression, cognitive avoidance, behavioural avoidance and loneliness form a sequential pathway from depression to loneliness. The model demonstrated an excellent fit to the data, χ^2 (2) = 2.753, p = .253.

As shown in Table 16 and Figure 27, the model revealed a significant total effect of depression on loneliness, β = .571, *SE* = .167, z = 8.943, p < .001. The direct effect of depression on loneliness remained significant, β = .432, *SE* = .179, z = 6.292, p < .001, indicating partial mediation. The indirect sequential effect through cognitive and behavioural avoidance was also significant, β = .139, *SE* = .088, z = 4.122, p < .001. All individual paths were statistically significant: depression was significantly associated with cognitive avoidance, β = .531, *SE* = .106, z = 8.137, p < .001; cognitive avoidance was positively linked behavioural avoidance, β = .748, *SE* = .049, z = 12.477, p < .001; and behavioural avoidance was positively associated with loneliness, β = .350, *SE* = .139, z = 4.873, p < .001.

Taken together, these findings indicate a sequential relation in which higher depression is linked to greater cognitive avoidance, which in turn is linked to greater behavioural avoidance, and these behaviours area associated with higher loneliness. In other words, cognitive and behavioural avoidance operate sequentially in the pathway from depression to loneliness, where maladaptive cognitive processes contribute to behavioural withdrawal, which ultimately contributing to high level of loneliness.

Table 16. Indirect and Total Effects in Serial Mediation Model: Depression, Cognitive Avoidance, Behavioural, and Loneliness

				95% C.I. (a)				
Type	**Path**	**Estimate**	**SE**	**Lower**	**Upper**	**β**	**z**	**p**
Indirect	**Depression ⇒ Cognitive ⇒ Behavioural ⇒ Loneliness**	0.362	0.088	0.200	0.540	0.139	4.122	<.001
Component	**Depression ⇒ Cognitive Avoidance**	0.870	0.106	0.663	1.077	0.531	8.137	<.001
	Cognitive Avoidance ⇒ Behavioural Avoidance	0.616	0.049	0.519	0.714	0.748	12.477	<.001
	Behavioural Avoidance ⇒ Loneliness	0.675	0.139	0.404	0.945	0.350	4.873	<.001
Direct	**Depression ⇒ Loneliness**	1.128	0.179	0.783	1.488	0.432	6.292	<.001
Total	**Depression ⇒ Loneliness**	1.490	0.167	1.167	1.821	0.571	8.943	<.001

Note. Confidence intervals computed with method: Standard (Delta method)

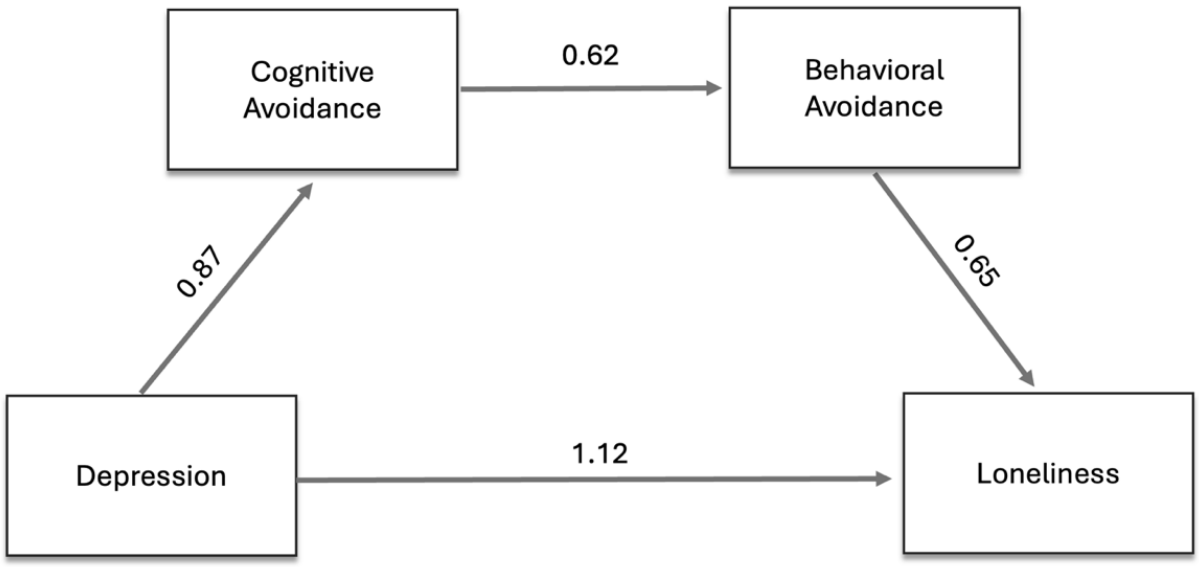


Figure 27. A Serial Mediation Model: Depression Predicts Loneliness via Cognitive and Behavioural Avoidance

3.4. Moderated Mediation of Depression, Avoidance, and Loneliness: Understanding the Buffering Role of Trust

Following the serial mediation, a moderated mediation analysis was conducted to test whether the relationship between depression and loneliness through avoidance was moderated by trust. The model demonstrated good fit to the data, χ^2 (3) = 4.62, p = .201.

As shown in the Table 17, depression was significantly associated with avoidance, β = 0.533, *SE* = 0.345, z = 8.656, p < .001. In turn, higher avoidance was significantly linked to higher loneliness, β = 0.632, *SE* = 0.056, z = 6.412, p < .001. The direct effect of depression on loneliness also remained significant, β = 0.314, *SE* = 0.072, z = 5.757, p < .001, suggesting partial mediation. Importantly, the interaction between avoidance and trust was significantly associated with loneliness, β = –0.388, *SE* = 0.012, z = –4.38, p < .001, indicating that trust buffered the association between avoidance and loneliness (Figure 28). Specifically, the negative coefficient suggests that positive association between avoidance and loneliness was weaker when trust is higher.

Table 17. Moderated Mediation Analysis of the Interaction Between Depression, Avoidance and Trust on Loneliness

			95% C.I. (a)				
Path	**Estimate**	**SE**	**Lower**	**Upper**	**β**	**z**	**p**
Depression ⇒ Avoidance	2.984	0.345	2.322	3.652	0.533	8.656	<.001
Avoidance ⇒ Loneliness	0.358	0.056	0.250	0.471	0.632	6.412	<.001
Depression ⇒ Loneliness	0.993	0.72	0.673	1.351	0.314	5.757	<.001
Avoidance * Trust ⇒ Loneliness	-0.052	0.012	-0.077	-0.030	-0.388	-4.38	<.001

Note. Confidence intervals computed with method: Standard (Delta method)

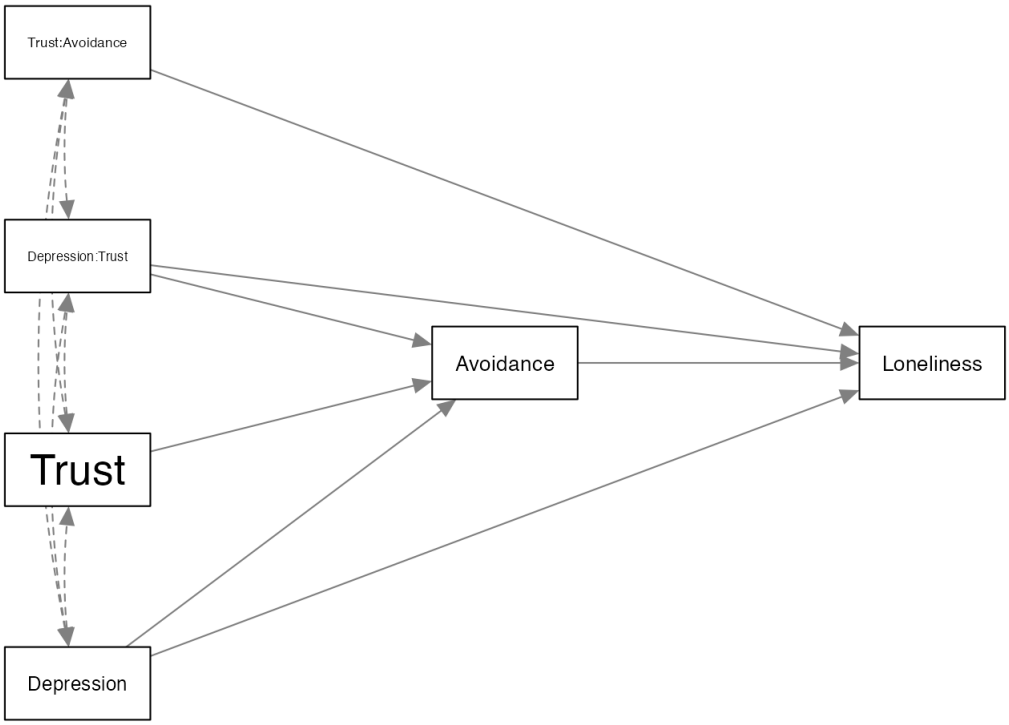


Figure 28. Moderated Mediation Model of Depression, Avoidance, Trust and Loneliness

Note. The model depicts a moderated mediation in which avoidance mediates the effect of trust and depression on loneliness, with the avoidance–loneliness pathway further moderated by trust and the depression–avoidance pathway moderated by trust.

4. Discussion

The present study explored the role of cognitive and behavioural avoidance in the association between depression and loneliness along with the potential buffering effect of trust in moderation this relationship. As of now, this is the first study exploring these relationships, and the findings provide valuable insights into how avoidance behaviours play a central role in linking depressive symptoms to increased feelings of loneliness, and that trust acts as a protective factor, buffering this association.

Consistent with a large body of previous research (Yuan et al., 2022; Kraav et al., 2021), and the findings from the Study 2b in this chapter, depression emerged as a significant predictor of loneliness, both directly and indirectly. However, the unique

contribution of this study is to extend the existing literature by demonstrating how cognitive and behavioural avoidance tendencies might explain the mechanism in this association. Particularly, individuals with higher depression level were concurrently associated greater avoidant social thoughts, which were in turn associated with higher levels of avoidant behaviours, and subsequently these behaviours were concurrently linked to higher level of loneliness. This result supports prior research suggesting that individuals with depression often avoid salient (e.g., personally meaningful or emotionally significant) or effortful tasks (mentally or physical demanding) which could deprive them of the opportunity to experience rewarding social interactions (Ottenbreit & Dobson, 2004).

Along with this, in the parallel mediation model, behavioural social avoidance emerged as the only significant mediator between depression and loneliness. Behavioural non-social avoidance also showed a significant indirect effect but in a negative direction. In contrast, cognitive social avoidance and cognitive non-social were not significant predictors of loneliness.

Behavioural social avoidance (e.g., avoiding people or withdrawing from social life) might lead to withdrawal from social settings by directly reducing opportunities for meaningful connections. This finding is quite interesting considering the limited findings from approach-avoidance bias in loneliness. As described in the Evolutionary Theory of Loneliness by Cacioppo and Hawkley (2009), lonely individuals experience simultaneous desire for connection (approach) and fear of rejection (avoidance). In this context, behavioural social avoidance represents the actualisation of this avoidance motivation in a visible, enacted withdrawal from social connections. From a neuroscientific perspective, this results map onto patterns of altered brain activity

observed in both individuals with high in loneliness and depression. For instance, the approach system (ventral striatum: reward system) was found underactive (Franco-O'Byrne et al., 2023; Uddin et al., 2017), while the avoidance system (amygdala) was found overactive (Morr et al., 2022a; Vitale & Smith, 2022), which may result in reduced motivation for and increased behavioural avoidance from social engagements. Moreover, as reported in Chapter 1, loneliness disrupts the reward and motivation system in the brain, leading to a diminished response to positive social interactions and a preference for non-social rewards, which could potentially further reinforce social withdrawal and isolation (Wong et al., 2022; Inagaki et al., 2016).

More importantly, depression compounds this neural imbalance by reducing motivation to positive social cues and increasing behavioural avoidance from social engagement. This might be because for individuals with depression, social interactions are less rewarding and more effortful (Solomonov et al., 2023). Perhaps, without adequate cognitive regulation from the PFC, which is responsible for cognitive control and emotion modulation, and found underactive in in depressed and lonely individuals in the early stages of information processing (Cacioppo & Cacioppo, 2015), individuals may find it difficult to override avoidance tendencies. In this way, depression may not only drive initial cognitive disengagement but also weaken the neural capacity to re-engage (Bowie et al., 2017), which leads behavioural avoidance to become the dominant coping strategy.

Meanwhile, behavioural non-social avoidance (e.g., avoiding obligations or withdrawing from demands) showed a significant negative indirect effect. This pattern may reflect an adaptive and protective function for individuals with depression to regulate their emotions or temporary relief that buffers against loneliness when social

interactions feel effortful or threatening. In fact, this aligns with broader psychological research suggesting that not all avoidance is inherently maladaptive, its context and function matter (Ball & Gunaydin, 2022; Krypotos et al., 2015). In terms of non-significant result between loneliness and cognitive avoidance, both social and non-social, they might be due to the fact that cognitive processes are internal strategies that do not necessarily disrupt outward behaviours. For instance, a lonely individual might mentally avoid distressing thoughts but still may engage in social gatherings and maintain relationships. Hence, this finding may indicate that cognitive avoidance is not sufficient to increase the level of loneliness unless it translates into observable behavioural withdrawal.

Moreover, the findings from the serial mediation model offer novel insight into the psychological pathway through which depression contributes to loneliness, highlighting the sequential roles of cognitive and behavioural avoidance. Specifically, individuals with high level of depression were more likely to engage in cognitive avoidance (e.g., suppressing or disengaging from distressing thoughts), which subsequently predicted increased behavioural avoidance. In turn, behavioural avoidance (e.g., withdrawing from social situations or avoiding communication) significantly predicted increased loneliness. This suggests a cascade of disengagement, in which internally focused avoidance strategies evolve into externally enacted withdrawal from social interactions. The result on the direct effect of depression on loneliness remaining significant after including both mediators indicates partial mediation, points to other affective or cognitive mechanisms (e.g., hopelessness, rejection sensitivity, negative self-schemas) which contributes to loneliness.

Finally, the moderated mediation model adds a crucial social dimension to these findings by demonstrating that the link between avoidance and loneliness is buffered by trust. This is a valuable insight because even when individuals engage in avoidance, holding more positive expectations about others' intentions may prevent the progression into chronic loneliness and act as a protective social belief. Trust may function as a social buffer, allowing individuals to retain hope in the benevolence of others, and increasing the likelihood of re-engaging after periods of withdrawal. This is consistent with evolutionary perspectives on loneliness, which suggest that social pain evolved to motivate reconnection but only when safety and trust in the social environment is perceived (Cacioppo et al., 2010). Hence, trust serves as a foundational prerequisite for social approach behaviour, and its presence can moderate the emotional costs of avoidance.

Taken together, these findings provide multi-level model of the depression-loneliness relationship demonstrating that this link is not only emotional but also cognitive and behavioural. Avoidance, particularly in behaviourally social contexts, serves as a key mechanism by which depression deprives individuals of protective social connections. However, this pathway is not inevitable. The presence of trust appears to buffer the damaging effects of avoidance, providing a potential intervention target for breaking the depression–loneliness cycle through behavioural activation and compassion-focused or trust-enhancement interventions.

Despite offering novel insights, several limitations should be acknowledged. For instance, cross-sectional design limits causality or temporal ordering, hence longitudinal designs are needed to test the sequential pathway. Moreover, self-report data cannot adequately distinguish between thoughts about avoidance and actual

behavioural withdrawal. To address this gap, future research should incorporate behavioural tasks measuring real-time behavioural avoidance in real-life scenarios, such as immersive VR paradigms

5. Conclusion

This is the first study in the literature examining how cognitive and behavioural avoidance sequentially mediate and how trust moderates the well-established relationship between depression and loneliness. Overall, the findings highlight that individuals high in depression are not only prone to have cognitive distortions with avoidance strategies, but they are also more likely to translate these into overt behavioural avoidance which ultimately increase the level of loneliness. Cognitive avoidance was correlated with loneliness but did not significantly mediate the depression and loneliness link, suggesting its influence operates through subsequent behavioural avoidance. Moreover, trust emerged as a key protective factor where individuals with higher level of generalised trust were less likely to experience increased loneliness which potentially could enable them to re-connect with others. These findings underscore the importance of targeting cognitive behavioural avoidance in therapeutic settings to strengthen interpersonal trust and break the depression-loneliness cycle.

Chapter Conclusion

In conclusion, the three studies presented in this chapter offer an integrated and nuanced understanding of the complex phenomenon of loneliness by examining its sociodemographic, psychological, behavioural, and social underpinnings.

Study 2a demonstrated that certain structural and situational factors, such as younger age, living alone or in a shared housing, being single or separated, and being homemaker or unemployed, are significantly associated with higher levels of loneliness. These findings point to critical life-stage vulnerabilities and the importance of daily social contexts in shaping the experience of loneliness. In contrast, biological sex, education, and ethnicity did not emerge as significant predictors, suggesting that psychological and relational variables may play a more central role.

Building upon this, *Study 2b* showed that individual differences in emotional processing and mental health symptoms, specifically alexithymia, depression, and social anxiety, were significantly associated with increased level of loneliness through both direct and indirect pathways. The study revealed that alexithymia not only contributes to loneliness independently but also operates through increased depression and social anxiety levels, both of which intensify withdrawal and disconnection. Importantly, social anxiety moderated the relationship between depression and loneliness, such that higher social anxiety amplified this association, where individuals with increased social anxiety reported higher loneliness at higher level of depression.

Finally, *Study 2c* expanded this framework by uncovering the behavioural pathways through which depression might potentially contribute to loneliness. Avoidance, particularly behavioural social avoidance, was identified as key a mediator, forming a cascade from internal disengagement to overt withdrawal. Moreover, trust emerged as a protective factor, buffering the negative effects of avoidance on loneliness and suggesting that interpersonal trust might reduce the impact of avoidance on loneliness.

Taken together, these three studies demonstrate that loneliness is not a result of a single factor, but rather a multi-determined experience shaped by the interaction between individual characteristics, emotions, thoughts, and behaviours. This multi-level model offers a robust foundation for understanding loneliness and paves the way for the experimental investigations in the next chapters, where these dynamics will be further explored in ecologically valid and immersive contexts.

CHAPTER 4

STUDY 3

Attention and Interpretation Bias in Facial Emotion Processing in Loneliness

"Your face is a book, where people may read strange matters."
William Shakespeare

Chapter Introduction

Cognitive biases, particularly attention and interpretation biases, have been increasingly associated with loneliness (Spithoven et al., 2017). Given that facial expressions are a primary mode of social communication (Durán & Fernández-Dols, 2021), examining how lonely individuals decode these emotional cues is crucial for how such biases develop and potentially intensify loneliness, particularly during sensitive developmental stages such as adolescence (Goossens, 2018). Thus, this chapter explored how individuals with varying levels of loneliness (high vs low) process facial emotions, using both dynamic and static face stimuli, to investigate attention and interpretation biases across ages.

To begin this investigation, *a pilot study* (N = 20) tested the feasibility of two online facial emotion processing tasks in adult sample including both morphed videos and static images. Emotion onset perception, decoding accuracy and interpretation of neutral faces were measured while also considering depression, social phobia, and alexithymia as potential confounds.

Building on these initial findings from the pilot study, *Experiment 1* (N = 366) was designed to examine the role of loneliness and age groups in attentional sensitivity (reaction time for correct responses) and decoding accuracy (correct categorisation of emotional valence). Participants from four age groups, adolescent, young, middle age and older adults, completed a facial emotion processing task with morphed video stimuli matched to participants' age group.

Informed by these findings, *Experiment 2* (N = 389) investigated interpretation biases towards ambiguous and neutral facial emotions which is a research field with limited empirical investigation in the literature. The experiment presented static images of neutral faces to measure misinterpretation and faces varying in emotional intensity (25%, 50%, 75%) to measure decoding accuracy across age groups.

In both, experiments, analyses controlled for key covariates: depression, social interaction anxiety and alexithymia, to ensure that observed effect were more specifically attribute to loneliness.

Together, these studies contribute to our understanding of how loneliness influence cognitive processing of facial emotions throughout the lifespan and emphasise the importance of adopting a developmental perspective while studying cognitive biases in loneliness.

Pilot Study

Expressions of interest: Exploring cognitive biases in facial emotion processing in loneliness[4]

Abstract

The current pilot study aimed to explore cognitive biases in lonely individuals, particularly in facial emotion processing. We recruited 20 participants (60% female, M_{age} = 36.8 years) to test the feasibility of two online tasks that assess the relationship between loneliness and facial emotion perception and interpretation, using age-matched faces. Task 1 measured the speed of emotion onset perception and decoding accuracy using morphed videos, while Task 2 examined the interpretation of neutral faces using static images. These complementary tasks allowed for a nuanced assessment of temporal dynamics of emotion perception and the interpretation of ambiguous facial emotion cues. Importantly, we controlled for depression, phobia and alexithymia. Loneliness was measured with the UCLA loneliness scale, and feedback on task experience was collected from participants. Findings indicated no significant effect of loneliness on emotion onset perception; however, social phobia and alexithymia emerged as predictors of loneliness, suggesting these factors may impact on emotional processing in lonely individuals. Additionally, participants interpreted neutral faces as sad significantly more than other emotions, but loneliness did not reach significance. While pilot participants suggested useful changes overall, the study supported the feasibility of this online setup for further investigation into cognitive biases in loneliness.

[4]*This pilot study has been published in a peer-reviewed British Psychological Society journal: Kiyak, C., Edwards, G., & Bengtsson, S. L. (2024). Expressions of interest: Exploring cognitive biases in facial emotion processing in loneliness. Psypag Quarterly, (126). DOI: https://doi.org/10.53841/bpspag.2024.1.126.19*

1. Introduction

Loneliness is characterised by a perceived gap between desired and actual social relationships (Zysberg, 2012). In the UK, around 3.7 million people report feeling lonely often or always (Campaign to End Loneliness, 2023). Chronic loneliness is linked to mental health issues such as depression and anxiety, and physical health problems like elevated blood pressure, poor sleep, and even increased mortality (Office for National Statistics, 2022).

Cacioppo et al. (2014) proposed that loneliness evolved to act as a signal to repair social connections necessary for survival, yet it also triggers hypervigilance for social threats. A greater understanding of how loneliness affects emotional and cognitive processes is therefore relevant to facilitate social interactions (Guarnera et al., 2023). Typically, these processes were studied with facial emotional processing paradigms, yielding mixed results so far. Some studies reported that lonely individuals were better at correctly recognising angry faces (Lodder et al., 2016), and demonstrated increased sensitivity to negative faces, such as sad and fear (Vanhalst et al., 2017). Meanwhile Bangee and Qualter (2018) reported that lonely adults demonstrate no attention biases for any facial emotion, however loneliness was associated with an initial orientation to angry faces rather than happy faces. Studies also suggested that lonely individuals misattribute neutral faces as sad (Cheeta et al., 2021).

Given these mixed findings, a pilot study was conducted employing both morphed videos and static images, enabling an in-depth investigation into the temporal dynamics of emotion perception and the interpretation of ambiguous facial expressions. This

evaluation provided a more robust investigation into the specific cognitive biases associated with loneliness. We addressed the following research questions:

RQ1. Are high-lonely individuals faster and more accurate in identifying negative facial emotion expressions (fear and sad) than positive facial emotion expressions (happy) when viewing morphed videos compared to low-lonely individuals?

RQ2. Are high-lonely individuals negatively biased in interpreting neutral facial expressions?

RQ3. How satisfied are participants with their experience in participating in this study?

2. Methods

2.1. Participants

20 participants (12 females, M_{age} = 36.8, *SD* = 11.5; range 25-79 years) were recruited online on a web-based experiment software *"Gorilla"*. Participants were allocated to age-matched facial emotion tasks (young: 18 – 35 years old; middle aged: 36 – 62 years old; older: 63 and over). Eligibility criteria were being over 18 years old, and fluency in English. The study was approved by the UEA PSY ethics committee *(Ethic ID: ETH2223-1331)* and adhered to APA ethical guidelines (Young, 2017) and the Declaration of Helsinki (World Medical Association, 2013).

2.2. Materials and Measures

Face Dataset: We used a face dataset with colour morphed videos and static images from the Center for Lifespan Psychology, Max Planck Institute for Human Development, Berlin, Germany (Ebner et al., 2010). The dataset included 18 actors (6

young, 6 middle-aged, 6 older), each presenting four facial emotions (happy, sad, fear, neutral).

Demographic Variables: Participants completed a questionnaire collecting socio-demographic information on biological sex, age, education level, employment status, relationship status, living condition, and ethnicity.

Loneliness: The UCLA Loneliness scale with 20 items (Version 3; Russell, 1996) was used to measure loneliness (α = .91). High and low levels of loneliness were determined by categorising individuals based on a median split of their total scores.

Depression: We used the Center for Epidemiologic Studies-Depression scale (Ces-D; Radloff, 1977), which comprises of 20 items assessing the experience of depressive symptoms during the past week (α = .86).

Social phobia: We used the Social Phobia Inventory (SPIN; Connor et al., 2000), which consists of 17 items that measure characteristics of social anxiety consisting of fear, avoidance, and physical reactions (α = .97).

Alexithymia: We used the Toronto Alexithymia Scale (TAS-20; Bagby et al., 1994), which includes 20 items covering difficulty identifying feelings, difficulty describing feelings to others, and externally oriented thinking (α = .79).

2.3. Procedure

After consenting and responding the demographic questionnaire, participants completed the facial emotion processing tasks, followed by the loneliness, depression, social phobia and alexithymia scales (Figure 29). The randomization was generated by the software at the beginning of each block, ensuring that each participant experienced a unique trial sequence.

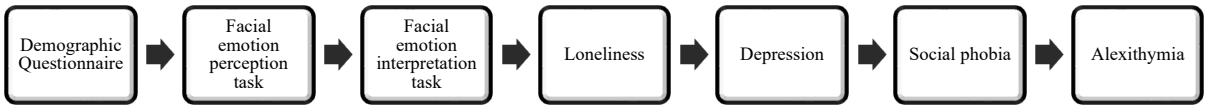


Figure 29. The Experiment Flow for Pilot Study

Task 1 – Facial Emotion Perception: Participants were presented with a balanced set of facial emotion expressions to mitigate potential overexposure bias: 12 happy (positive) faces, 6 fear and 6 sad (negative) faces. Each trial began with a 250 ms fixation cross, followed by a 10 second morphed video where a neutral face morph into a full emotion. Participants were asked to press the spacebar as soon as detecting an emotion to measure "emotion perception onset (reaction time)" and subsequently report if the expression was "Positive" or "Negative" to measure "decoding accuracy" (Figure 30). They completed 28 trials (4 practice, 24 test).

Task 2 – Facial Emotion Interpretation: Participants were presented with four different facial emotion expressions: 48 happy (positive) faces; 24 fear and 24 sad (negative) faces; and 24 neutral faces. Each trial began with a 250 ms fixation cross, followed by a 400 ms static image of an emotion. Subsequently, the participants selected the emotion they think they saw among four options, "Happy", "Surprised", "Fear", and "Sad" (Figure 30). They completed 124 trials (4 practice, 120 test).

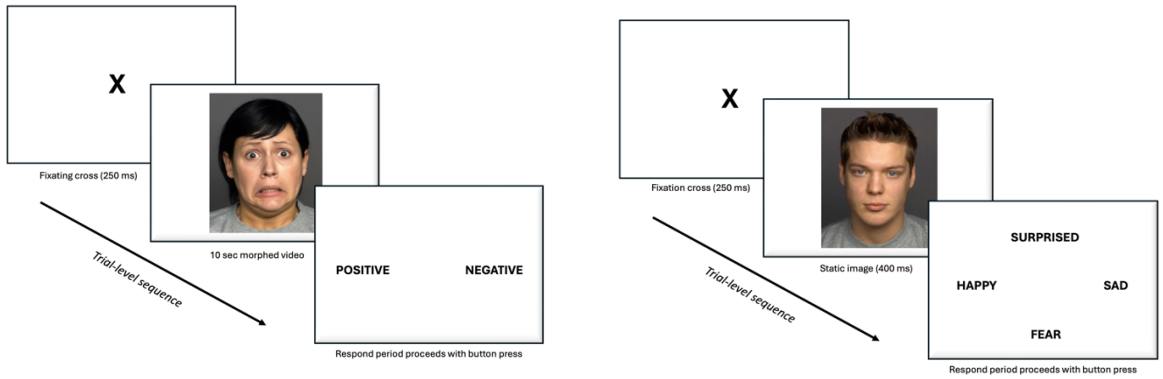


Figure 30. Schematic Presentation of the Experimental Procedure for Task 1 (left) and Task 2 (right)

2.4. Analysis

For Task 1, a 2x2 mixed-design ANOVA, with the loneliness group (High-lonely vs. Low-lonely) as the between-subjects factor and emotion type (positive vs. negative or fear vs. sad) as the within-subjects factor, was conducted to analyse emotion onset perception (reaction times for detecting emotion onset) and decoding accuracy (the percentage of correctly identified target emotion). For Task 2, a 2x4 mixed-design ANOVA assessed neutral face interpretation (the percentage of each emotion reported when seeing neutral faces), with loneliness group as the between-subjects factor and emotion type (happy, surprised, fear, sad) as the within-subjects factor. Depression, social phobia, and alexithymia scores were controlled as confounding variables in both analyses.

3. Results

3.1. Emotion Onset Perception (Reaction Time)

The analysis revealed no significant interaction between emotion and loneliness, F (1, 15) = 0.65, p = 0.434, nor a main effect of emotion on reaction time, F (1, 15) = 0.03, p = 0.868. Moreover, neither loneliness, F (1, 15) = 0.02, p = 0.887, nor depression, F (1, 15) = 0.002, p = 0.968, affected reaction times. However, social phobia and alexithymia were significant predictors, yielding F (1, 15) = 5.35, p = 0.035 and F (1, 15) = 8.27, p = 0.012, respectively. No significant interaction was found between fear and sad faces in relation to loneliness, F (1, 15) = 0.930, p = 0.350, however, social phobia F (1, 15) = 8.847, p = 0.009 and alexithymia F (1, 15) = 8.561, p = 0.010 remained significant (Figure 31).

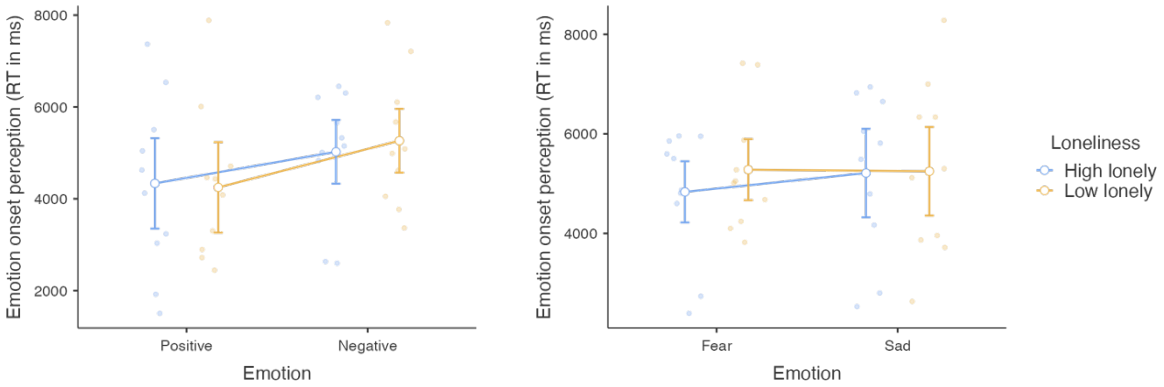


Figure 31. Reaction Times in Milliseconds to Facial Emotions by Loneliness Levels

Note. Comparing positive vs negative (left) and fear vs sad (right) emotions, with individual data points and 95% confidence intervals to illustrate participant variability and the precision of mean estimates.

3.2. Decoding Accuracy

There was no significant interaction between loneliness and facial emotion F (1, 15) = 1.898, p = 0.189, nor a main effect of emotion F (1, 15) = 0.189, p = 0.670, or loneliness F (1, 15) = 0.005, p = 0.944. However, social phobia emerged as a significant predictor of loneliness, F (1,15) = 5.923, p = 0.028. Further analysis of difference between fear and sad

also showed no significant main or interaction effects (all p > 0.3), with accuracy not differing between high and low lonely individuals (Figure 32).

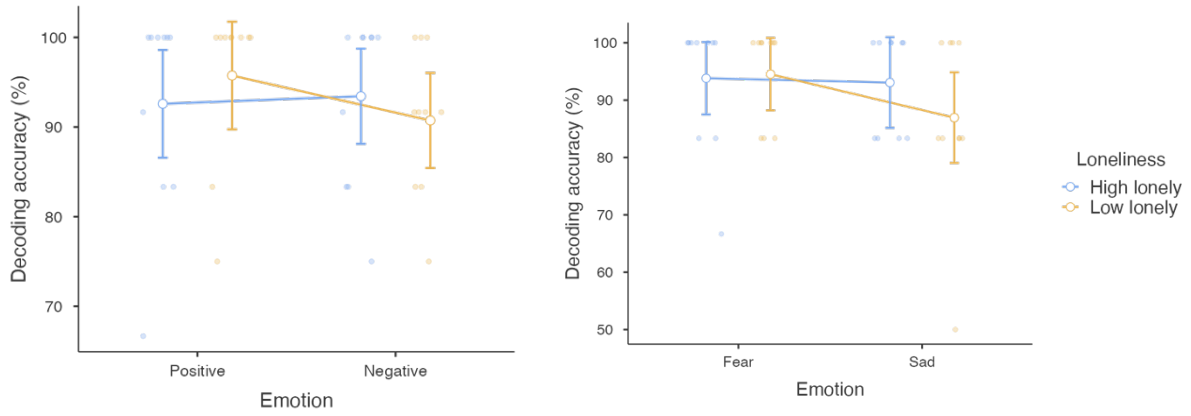


Figure 32. Decoding Accuracy in Percentages for Facial Emotions by Loneliness Levels

Note. Comparing positive vs negative(left) and fear vs sad (right) emotions, with individual data points and 95% confidence intervals to illustrate participant variability and the precision of mean accuracy estimates.

3.3. Interpretation of Neutral Faces

There was a significant main effect of emotion on the interpretation of neutral faces, F (3,45) = 13.79, p < .001. However, there was no significant interaction between emotion and loneliness, F (3,45) = 1.20, p = .320, nor a significant main effect of loneliness on the emotions, participants attributed to neutral faces, F (1,15) = -0.014, p = 1.000. Post-hoc tests showed that both high and low lonely participants attributed neutral faces as sad faces significantly more than happy (t (15) = -10.31, p < .001), surprised (t (15) = -10.20, p < .001), and fear faces (t (15) = -14.87, p < .001). The estimated marginal means further supported this finding, with sad being the most frequently attributed emotion to neutral faces in both high lonely (M = 78.84, SE = 5.59) and low lonely (M = 69.91, SE = 5.59) groups (Figure 33).

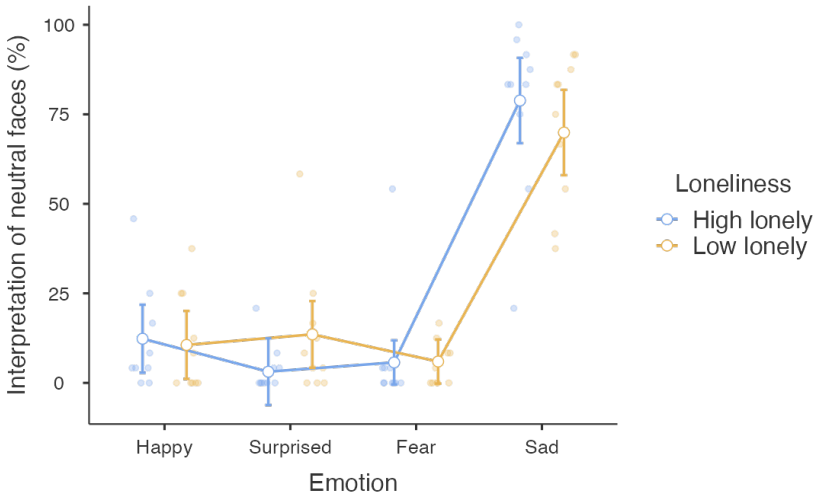


Figure 33. The Interpretation of Neutral Faces by Loneliness Levels and Emotions

Note. With rating frequencies in percentages, individual data points and 95% confidence intervals to illustrate participant variability and precision of mean estimates for each emotion across different loneliness levels.

3.4. Qualitative Analysis on the Feasibility of the Experiment

Most participants found Task 1 to be of moderate length, while opinions on Task 2 varied more, with several participants finding it too long. Participants reported that the need to click the 'next' button frequently disrupted their concentration and overall flow of the experiment on Task 2. Some participants mentioned the lack of option for certain emotions, such as a neutral face, indicating a potential flaw in the emotional categorisation used. The overall responses suggested a need to shorten Task 2 and introduce a "neutral" button option, to improve participant experience, while the instructions appear to be clear and effective. The questionnaires were described as overly lengthy and complex, further contributing to participant fatigue. In conclusion, while the study was acknowledged as interesting, these insights highlight critical areas for adjustment to improve participant experience and data reliability.

4. Discussion

This pilot study explored how loneliness impacts the perception and interpretation of facial emotions, focusing on emotion onset, decoding accuracy, and neutral face interpretation. The findings offer insights into the importance of taking related aspects into account, such as depression, social phobia, and alexithymia.

Based on a small sample-size, the results suggest no significant effect of emotion on reaction times, suggesting similar speed processing of positive and negative emotions across loneliness levels. This finding contrasts with research suggesting that negative emotions, especially anger and sad, are often detected faster than positive emotions (Cacioppo et al., 2014). Social phobia and alexithymia also predicted slower reaction times, aligning with research linking these factors to cautious emotional recognition due to social judgment fears (Lacombe et al., 2023; Grynberg et al., 2012).

Decoding accuracy results showed no significant main effect of emotion, indicating similar accuracy in recognizing positive and negative emotions across loneliness levels. This aligns with previous research suggesting loneliness does not impair the ability to recognise overt emotional cues (Bangee & Qualter, 2018). Moreover, social phobia significantly predicted lower decoding accuracy, pointing to perceptual biases in emotional recognition (Heuer et al., 2007).

An interesting observation was the significant effect of emotion on interpreting neutral faces as sad. This could align with the “negativity bias” where lonely individuals often evaluate ambiguous facial expressions negatively (Cheeta et al., 2021). Prior research indicates lonely individuals may view neutral expressions as signs of rejection

or hostility (Bangee & Qualter, 2018). However, the lack of an interaction between emotion and loneliness suggests this bias may be general rather than loneliness specific.

As a pilot study, the findings highlight both potential avenues and limitations for future research on loneliness and facial emotion perception. While the results offer preliminary insights, the small sample size likely reduced statistical power, limiting the generalizability of findings and the ability to detect nuanced interaction effects. Going forward, we plan to add a "neutral" button as an option for interpreting neutral faces and reduce the number of stimuli for Task 2, replace the questionnaires with shorter versions, and remove the "next" button between screens.

5. Conclusion

Overall, this pilot study is underpowered, and a larger sample size is necessary to obtain more reliable and generalizable results. However, the current results still underscore the complexity of facial emotion processing in lonely individuals. Future studies should continue to explore these dynamics, incorporating a larger and more diverse sample to enhance the generalizability of the findings.

Experiment 1

Attention and interpretation bias in facial emotion processing across ages in loneliness

Abstract

Loneliness has been linked to cognitive biases in facial emotion processing, particularly with attention and interpretation biases, yet this link across different age groups remains unclear. Therefore, the effects of loneliness on facial emotion processing across four age groups were investigated in a large cross-sectional sample: adolescent, young, middle-aged, and older adults (N = 366). The two key aspects of facial emotion processing were examined, *attentional sensitivity* and *decoding accuracy*, by employing morphed videos with age-matched stimuli and controlling for depression, social anxiety and alexithymia. The findings revealed a significant three-way interaction between loneliness, emotion type and age groups. Attentional sensitivity to positive emotions followed a non-linear developmental trajectory, with adolescents showing decreased sensitivity to positive faces, an increase in young and middle-aged adults, and a subsequent decrease in older adults. Meanwhile, older adults demonstrated a positive cognitive bias by decoding positive emotions more accurately than negative ones. Contrary to hypervigilance theories, loneliness did not uniformly lead to negative cognitive biases but demonstrated varying effects across age groups. Hence, this research underscores the complex interplay between loneliness, facial emotion processing, and age, suggesting that the impact of loneliness on facial emotion processing is dynamic and age dependent. The findings provide valuable insights that can guide the design of Cognitive Bias Modification (CBM) interventions that vary by age group by addressing these specific biases, both positive and negative, targeting lonely individuals. Future research should explore these effects using longitudinal designs and real-world social interaction paradigms, such as virtual social environments, to enhance ecological validity.

1. Introduction

Previous studies suggest that lonely individuals demonstrate cognitive biases that prioritise the processing of negative social cues over positive social cues and/or non-social cues due to self-preservation mechanism (Spithoven et al., 2017). Supporting this, according to the Scoping Review in Chapter 2, although findings are mixed, lonely individuals demonstrate *attention biases* that prioritise processing negative social cues over positive or neutral cues (Grennan et al., 2021; Du et al., 2022; Cacioppo et al. 2016), potentially reflecting self-preservation mechanisms (Spithoven et al., 2017). These inconsistencies across studies might have resulted from several methodological differences in the experiments, such as differences in sample size, stimulus type, experimental paradigms, confounding factors and age composition. In contrast, *interpretation bias* was more consistent cognitive bias linked to loneliness, particularly among adults, where they interpreted ambiguous cues more negatively (Edwards et al., 2001; Lau et al., 2021; Okruzsek et al., 2021; Nombro et al., 2022). The findings from the pilot study also provided new and contradictory insights. Specifically, loneliness and emotion had no significant effects on reaction time or decoding accuracy in processing facial emotions. However, both high and low lonely participants consistently interpreted neutral faces as sad, revealing a general negativity bias when processing ambiguous facial emotions. Together, these cognitive biases then reinforce loneliness through the behavioural confirmation process by validating their negative expectations of others, leading them to socially withdraw, which consequently perpetuates their loneliness (Skoko et al., 2024; Rotenberg et al., 2004).

Moreover, the findings from the multivariate modelling analyses in Chapter 3 further supported previous research by demonstrating strong correlations between loneliness, depression, social anxiety, and alexithymia, highlighting how these factors may contribute to cognitive biases in facial emotion processing.

However, while these cognitive biases have been investigated widely in adults, there is a huge gap in understanding how age-related differences could potentially influence cognitive and emotional processing in loneliness.

1.1. Cognitive Biases in Facial Emotion Processing in Loneliness

Facial emotions play a crucial role in social functioning, as they provide essential non-verbal cues that guide interpersonal communication and navigate complex social environments effectively (Guarnera et al., 2023; Adolphs, 2002). However, *cognitive biases* may negatively influence how people perceive and interpret facial expressions which convey important social and emotional information (Korteling et al., 2018; Korteling et al., 2023). Such biases may lead to cognitive distortions contributing to patterns of social interaction. For instance, previous literature posited that the aversive biological signal (e.g. threat, fear) of loneliness contributes to reduced arousal response to for both negative and positive affective stimuli (Cacioppo & Cacioppo, 2018; Wong et al., 2018). Further evidence suggested that lonely individuals have lower attentional control (e.g., focusing on positive emotions, ignoring socially irrelevant distractions, shifting attention away from ambiguous cues), compared to non-lonely individuals (Baumeister et al., 2005; Cacioppo et al., 2006; Cacioppo & Hawkley, 2009), which may impair their ability to effectively focus on relevant emotional cues.

Moreover, neurobiological studies demonstrated reduced volume and heightened activation in amygdala (Lam et al., 2021; Düzel et al., 2019); reduced volume and activation in PFC (Kiesow et al., 2020); alterations in the insular cortex (Finley et al., 2023); reduced volume and alterations in ventral striatum (Franco-O'Byrne et al., 2023; Uddin et al., 2017) in lonely individuals, These findings underpin the maladaptive characteristics of loneliness which may lead to negative cognitive biases, reduced social affiliation (and increased aversion), emotion dysregulation, and impaired social cognition (Franco-O'Byrne et al., 2023).

Taken together, this body of evidence indicates that loneliness can fundamentally disrupt both the attentional and interpretive mechanisms involved in facial emotion processing, potentially leading to maladaptive social perceptions.

1.2. Age-Specific Patterns in Facial Emotion Processing in Loneliness

Contrary to the common stereotype that loneliness is mainly a problem for older individuals, loneliness is experienced by people of all ages (Hawkley et al., 2022). Loneliness has been found to be highest in adolescents and then declines throughout middle adulthood, but then it increases in older age (Graham et al., 2024; Hawkley, 2022; Qualter et al., 2015). Therefore, the prevalence of loneliness across age groups, particularly its higher occurrence in adolescents and the older adults, highlights the potential for a broad impact on cognitive and emotional functions. Each life phase presents unique developmental changes (e.g., emotion regulation, cognitive flexibility, attentional control) from childhood to older adulthood which might affect how individuals process emotional and social information (Buecker et al., 2024).

As loneliness peaks during key transitional stages of life, such as adolescents and older adulthood, it is more likely to influence how individuals perceive and respond to facial emotion cues (Qualter et al., 2021; Hawkley & Capitanio, 2015).

As indicated in the Scoping Review in the Chapter 2, most empirical studies focused on middle-aged populations; only a few studies included adolescents and older adults, and none of them adopted a lifespan perspective. Among them, only one study investigated attention bias in facial emotion processing with morphed videos in adolescents where lonely adolescents demonstrated increased sensitivity to negative facial emotions (Vanhalst et el., 2017). Meanwhile, limited number of studies in adolescents for interpretation bias yielded mixed results reporting no interpretation bias (Vanhalst et al., 2017), and reduced accuracy for negative and increased accuracy for positive faces (Morningstar et al., 2020). However, there is a significant gap in the literature exploring how attention and interpretation bias might affect facial emotion processing across age groups. Thus, comprehensive research is needed to examine how attention and interpretation biases in facial emotion processing may reflect in lonely individuals across ages.

1.3. Experimental Design Rationale and Research Questions

Two experiments were rigorously designed with methodological refinements informed by the pilot study findings and feedback to address the critical gaps identified in the literature. So far, previous facial emotion processing studies mainly relied on static displays of facial emotions. However, while static images offer methodological precision, they lack the temporal and expressive richness of real-life emotional interactions (Krumhuber et al., 2007; Sato et al., 2004). Meanwhile, morphed videos

improve ecological validity by simulating the gradual development of facial emotions and provide a closer representation of dynamic social cues encountered in everyday life (Sato & Yoshikawa, 2007). Consequently, in the first experiment, morphed videos were employed. In the second experiment, we used static images. This multimodal approach allowed comprehensive assessment of facial emotion processing capturing both the temporal dynamics of emotion perception through morphed videos and interpretive aspects of ambiguous facial emotions through static images.

Moreover, changes were made for the two experiments, especially in Experiment 2, based on the qualitative feedback from the pilot study, to enhance both the participant experience and data reliability in the main experiments. Firstly, the keyboard arrow navigation was implemented for both experiments to address the repetitive need to click a 'next' button, which was identified as disruptive to focus and reaction time accuracy. This implementation allowed smoother and more automated reactions and reduced unnecessary hand motions. For the Experiment 2, a 'neutral' category was introduced to improve the accuracy of emotion classification, and the overall task was substantially shortened with a reduced number of face stimuli to minimise fatigue reported by the participants in the Pilot Study. Furthermore, facial emotions at 100% intensity were too easy and clear to process; hence, they were removed to only include ambiguous faces, which aligns better with the Experiment 2's goal to investigate interpretation biases. Some other alterations were made as well for the lengthy and redundant measures. For instance, the depression measure was replaced with a condensed version that maintained psychometric robustness. Similarly, the social phobia scale was replaced with more concise one which particularly measures social interaction anxiety. Lastly, two out of three subscales of the alexithymia questionnaire

were selectively chosen to reduce participant burden while preserving conceptual relevance to the research questions. These improvements aimed to enhance task engagement, reduce participant fatigue, and increase the ecological and psychological sensitivity of the two experimental designs.

Building upon these methodological refinements along with the insights gained from the pilot study and Scoping Review findings, the first experiment was designed to examine how attention and interpretation biases manifest across age groups. Hence, in the Experiment 1, the attentional sensitivity to facial emotions, to investigate attention bias, and decoding accuracy, to investigate interpretation bias, was measured across four age groups: adolescent, young, middle-aged, and older adults. The unique influence of loneliness on facial emotion processing was aimed to be isolated by controlling for covariates such as depression, social anxiety and alexithymia. This approach enabled us to reduce the variability and improve the robustness of the findings. We addressed the following research questions:

RQ1. How does loneliness influence attention bias in terms of attentional sensitivity to facial emotions across age groups when controlling for depression, social anxiety, and alexithymia?

RQ2. How does loneliness influence interpretation bias in terms of decoding accuracy in facial emotion processing across age groups when controlling for depression, social anxiety, and alexithymia?

2. Methods

2.1. Participants

A power analysis was conducted using GPower to determine the required sample size for detecting significant effects in the mixed-design ANOVA. The analysis was based on an expected medium effect size ($\eta^2 = .06$), $\alpha = .05$, and power ($1 - \beta$) = .80, resulting in a recommended sample size of 400 participants to ensure sufficient statistical power. Therefore, a total of 575 participants were assessed for eligibility in an online experiment. 170 participants were excluded due to ineligibility or non-completion, leaving 405 remaining participants. Following a data quality check, 39 participants were further excluded based on predefined criteria (see 2.2 below; Figure 34). The final sample consisted of 366 participants aged between 13 and 83 years, including 233 females (63%) and 133 males (37%). Participants were grouped into four age categories: adolescents (13–17 years), young adults (18–35 years), middle-aged adults (36–62 years), and older adults (63 years and above). This age categorisation followed the classification used in the facial stimuli dataset to ensure age-matched comparisons between participants and the presented faces (Ebner et al., 2010). Demographic characteristics of participants and descriptive statistics across these age groups are summarised in Table 18. Percentages are calculated within age groups.

Table 18. Participant Demographics and Descriptive Statistics (*N* = 366)

	Adolescent	Young	Middle age	Older
N	88	91	95	92
Age Mean (+/- SD)	14.61 (1.52)	23.84 (5.84)	46.66 (7.64)	67.94 (4.54)
Sex				
Female	56 (63.6%)	64 (70.3%)	59 (62.1%)	54 (58.7%)
Male	32 (36.4%)	27 (29.7%)	36 (37.9%)	38 (41.3%)
Education level				
Highschool	N/A	55 (60.4%)	35 (36.8%)	39 (42.4%)
Bachelor's degree	N/A	26 (28.6%)	46 (48.4%)	37 (40.2%)
Master's degree	N/A	10 (11%)	11 (11.6%)	10 (10.9%)
PhD	N/A	0	3 (3.2%)	6 (6.5%)
Employment				
Student	88	41 (45.1%)	0	0
Part-time employed	N/A	13 (14.3%)	21 (22.1%)	9 (9.8%)
Full-time employed	N/A	24 (26.4%)	39 (41.1%)	10 (10.9%)
Self-employed	N/A	4 (4.3%)	20 (21.1%)	14 (15.1%)
Homemaker	N/A	0	3 (3.2%)	2 (2.2%)
Retired	N/A	0	6 (6.3%)	57 (62.0%)
Unemployed	N/A	9 (9.9%)	3 (3.2%)	0
Living condition				
Alone	0	15 (16.5%)	10 (10.5%)	19 (20.6%)
With parents	85 (96.5 %)	20 (22.0%)	4 (4.2%)	0
With other family members	3 (3.5%)	4 (4.4%)	9 (9.5%)	11 (12.0%)
With friends or shared house	0	34 (37.4%)	3 (3.2%)	0
With partner/husband/wife	0	18 (19.8%)	69 (72.6%)	62 (67.4%)
Relationship status				
Single	N/A	39 (42.9%)	17 (17.9%)	13 (14.1%)
In a relationship	N/A	43 (47.3%)	18 (18.9%)	8 (8.7%)
Married	N/A	8 (8.8%)	55 (57.9%)	61 (66.3%)
Separated	N/A	1 (1.1%)	2 (2.1%)	3 (3.3%)
Divorced	N/A	0	3 (3.2%)	7 (7.6%)
Ethnicity				
White	71 (80.6%)	58 (63.7%)	77 (81.1%)	91 (98.9%)
Black or Black British - African	2 (2.3%)	11 (12.1%)	10 (10.5%)	0
Asian or Asian British - Indian	2 (2.3%)	5 (5.5%)	3 (3.2%)	0
Chinese	3 (3.4%)	3 (3.3%)	2 (2.1%)	0
Mixed - White and Asian	3 (3.4%)	4 (4.4%)	0	0
Arab	2 (2.3%)	4 (4.4%)	0	0
Any Other Ethnic Background	5 (5.7%)	6 (6.6%)	3 (3.1%)	1 (1.1%)
Scales				
Loneliness Mean (+/- SD)	13.34 (5.14)	48.35 (11.91)	46.90 (12.84)	40.31 (11.78)
Depression Mean (+/- SD)	8.22 (6.01)	12.30 (6.16)	9.73 (6.30)	7.55 (7.14)
Social Anxiety Mean (+/- SD)	22.34 (7.55)	8.78 (4.92)	5.70 (5.01)	3.30 (3.30)
Alexithymia Mean (+/- SD)	19.53 (6.00)	31.45 (10.48)	26.20 (9.87)	24.23 (8.31)

2.2. Data Quality Check

Step 1: The accurate responses represent reliable cognitive processing rather than random noise or measurement error (Zorowitz et el., 2023). Therefore, attentional sensitivity was computed by averaging reaction times (RT) for correct responses to ensure the validity and reliability of the data in the investigation of facial emotion processing (Ratcliff, 1993). This approach is in line with theoretical viewpoints that sensitivity is a single crucial parameter combining speed and accuracy in the study of emotional processing, which focuses on participants' ability to correctly discriminate between positive and negative valence (Draheim et al., 2019; Huang & Luo, 2006). Following this, participants whose reaction times were more than 10 seconds for either positive or negative stimuli were excluded because such prolonged reaction times indicate task disengagement, confusion, or technical issues, rather than reliable emotion processing, as morphed videos last 10 seconds (Wood et al., 2017). Moreover, the integrity of the valence-based comparison, which is critical to examining negative cognitive bias, was preserved by excluding these participants (Baumeister et al., 2001). Consequently, only participants were included who followed task instructions and engaged with them within the given time frame to reduce noise in the data.

Step 2: A second exclusion criterion was introduced as well to further refine the dataset targeting participants who scored below-chance accuracy levels for decoding accuracy measurement. Since accuracy *at* or *below* chance level in binary-choice tasks (positive vs negative) usually reflects insufficient attention or a lack of adherence to task instructions, a score below 50% suggests random guessing or task disengagement (Ratcliff, 1993). This step was essential to ensure that participants who were retained

not only completed the trials by stopping the morphed video as soon as they saw an emotion within the given time frame but also showed that they were engaged with the stimuli during the selection of a valence. As in Step 1, this criterion also ensured that participants in the final analysis demonstrated reliable engagement with stimuli, allowing for a valid assessment of valence-specific effects. Hence, integrity of the dataset was further improved by employing this accuracy threshold in combination with the reaction time exclusion criteria, which provided responses that are both accurate and timely (Newman et al., 2021). According to Etkin et al. (2011), this data quality approach aligns with best practices in face emotion processing research, where participant performance criteria are commonly used to ensure reliable measures of attentional sensitivity and cognitive engagement with valanced stimuli.

Step 3: Finally, outlier detection was carried out using a ±3 standard deviation (SD) criterion for reaction times after completing Step 1 and 2. Reaction times that are more than ±3 SD from the mean were removed since these extreme values potentially reflect atypical responses caused by distraction, misunderstanding of the task, or technical errors (Smiti, 2020). The ±3 SD criterion is widely regarded as a robust technique for outlier detection, capturing approximately 99.7% of a normally distributed dataset and removing only the most extreme deviations (Field, 2018). This approach enhances the reliability of reaction time analysis ensured with the remaining data which reflect the typical response patterns of participants. In facial emotion processing research, removing outliers is particularly important, where extreme values could disproportionately affect mean reaction times and skew comparisons across valence categories, which could result in inaccurate conclusions about biases (Leys et al., 2013).

Taken together, these three steps in the data quality check, removing (1) RTs beyond stimulus duration, (2) below-chance accuracy scores, and (3) outliers, ensured a high-quality dataset with timely, reliable, and consistent engagement with the tasks. Hence, the integrity and robustness of the analyses examining valence-specific effects in facial emotion processing were preserved (Figure 34).

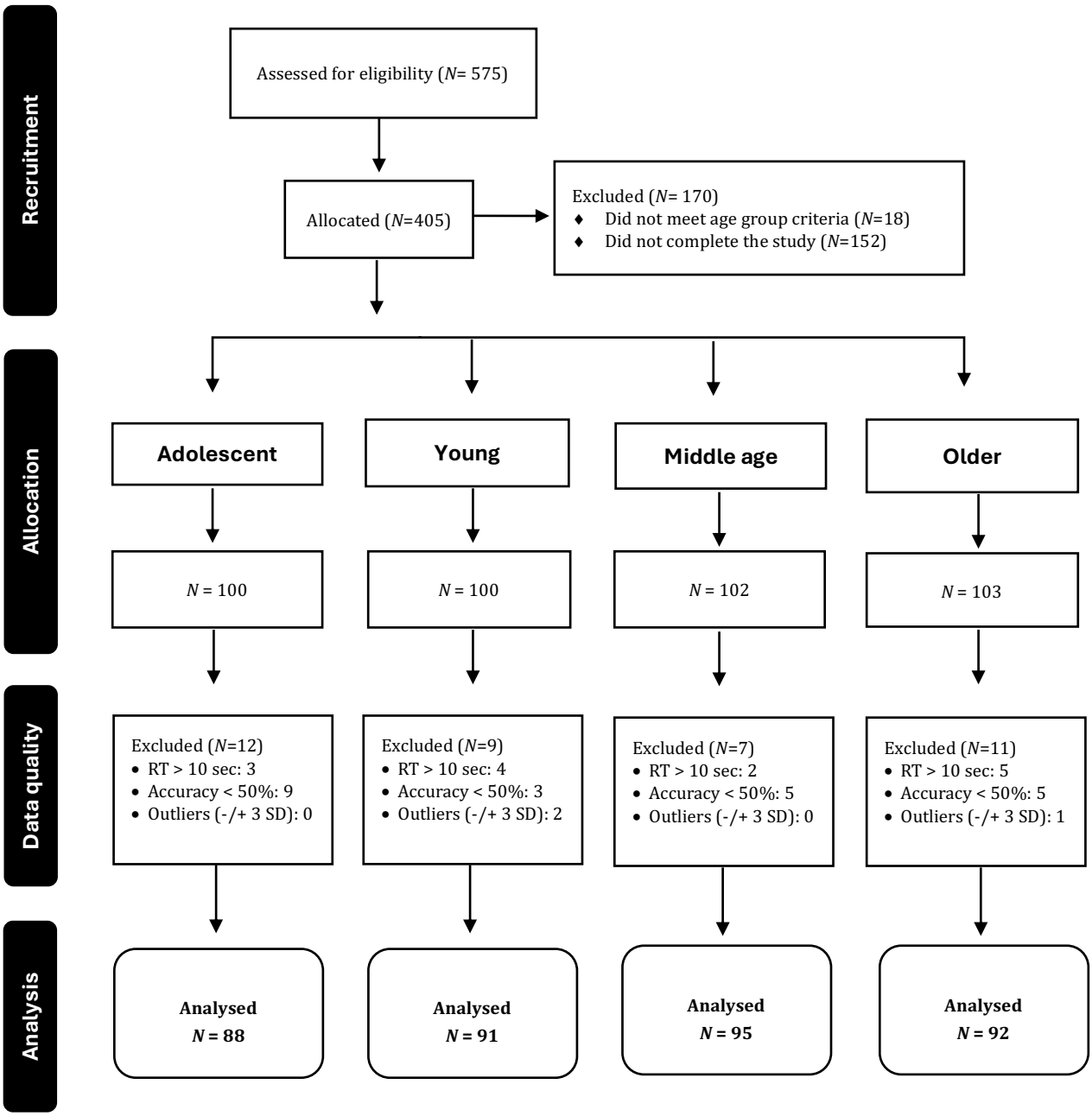


Figure 34. Flowchart Illustrating Participant Recruitment, Allocation and Data Quality Procedures

2.3. Materials and Measures[5]

For the studies in this chapter, the age-appropriate measures were used, including face datasets and scales, for both adolescents and adults to ensure the validity and suitability of assessments across different age groups. The methodological choice of using age-appropriate face datasets was grounded on the well-established phenomenon of *the own-age bias* in facial emotion processing which suggests that people are better at identifying emotions from faces within their age range (Pizzio et al., 2022). Recent studies further emphasised the significance of age-congruent stimuli in emotion recognition tasks. For instance, Brouwer et al. (2021) demonstrated that using age-appropriate face stimuli significantly reduces the own-age bias effect and provides a more accurate assessment of emotion recognition abilities across different age cohorts. For this reason, the age of the facial stimuli was matched with the age group of the participants to control for its asymmetrical influence across age groups, to mitigate the potential confounds and enhance a more ecologically valid experimental environment.

Moreover, to mitigate the other potential confounding effects arising from using distinct scales for adolescents and adults, which could potentially compromise the comparability of the results across age cohorts (Colan et al., 2013), *z*-score standardisation was employed. This statistical transformation allowed to convert the

[5] *The two studies presented in this chapter are based on the data from the same original online experiment, using the same initial pool of participants, same OSF registration, ethical approval, face datasets, measures, and experimental setup. However, due to variations in data quality check and task-specific requirements (Study 1 includes morphed videos, and the Experiment 2 includes static images), the final samples slightly differ across the two studies. Consequently, the total number of participants and specific measurements included in each analysis vary accordingly. To avoid replication, detailed descriptions of shared measures and materials will not be repeated in the Experiment 2 unless they are different from those reported in the Experiment 1.*

incomparable scale scores into a standardised metric, thus facilitating more robust cross-age comparisons and enhancing the internal consistency of our findings.

Participants were also categorised as "high" or "low" lonely using a median split on loneliness scale scores for a balanced sample size between the two categories which is supported by the literature (Iacobucci et al., 2015).

2.3.1. Materials and Measures for Adolescents

Face dataset: The validated NIMH Child Emotional Faces Picture Set (NIMH-ChEFS; Egger et al., 2011) was used for the adolescent group. A total of 12 models (6 girls, M_{age} = 13.00 year, *SD* = 1.79; 6 boys, M_{age} = 14.17 year, *SD* = 1.47) were selected from this set. The morphed video clips were shortened from 20 sec to 10 sec by speeding them up in iMovie software (Apple Inc., 2025). The size of the video clips was 19.5 x 21.5 cm. Due to the unavailability of the coloured version in open-access resources, grey-scale morphed videos and images were used for the adolescent group.

Demographic variables: All participants completed a questionnaire to collect sociodemographic variables such as age, biological sex, education, living condition, and ethnicity.

Loneliness: Loneliness level was assessed using a 5-item abbreviated adaptation of the Loneliness and Social Dissatisfaction Questionnaire which was developed to measure children's level of loneliness (LSDQ; Cassidy & Asher, 1992). Participants indicated the extent to which they had felt lonely in the last year (e.g., "*I felt alone*," "*I was sad and alone*") on a 5-point Likert scale (1 = *never* to 5 = *very often*). The scale ranges from 5 to 25, and exploration of cut-off scores is also recommended, as no established thresholds

currently exist for this measure (Cole et al., 2021). Internal consistency in this study sample was excellent (α= .95).

Depression: The Short Mood and Feelings Questionnaire (SMFQ; Angold et al., 1987) is a 13-item questionnaire that measures depressive symptoms in children and adolescents, mainly assessing affective and cognitive symptoms. Participants rated their feelings over the past two weeks on a 3-point Likert scale (0= *not true, 1 = sometimes,* 2 = *true*). The total score ranges from 0 to 26, and a cut-off score of 12 or indicates significantly depressive symptomatology. Internal consistency in this study sample was excellent (α= .90).

Social anxiety: The 8-item fear of negative evaluation subscale of the Social Anxiety Scale for Adolescents (SAS-A; La Greca & Lopez, 1998) was used to assess social anxiety among adolescents on a 5-point Likert scale (1 = *not true* to 5 = *always true*). Total scores range from 8 to 40. Internal consistency in this study sample was excellent (α= .92).

Alexithymia: Toronto Alexithymia Scale for Adolescents (TAS-20; Bagby et al., 1994) consists of three dimensions: difficulty identifying feelings (DIF; 7 items), difficulty describing feelings (DDF; 5 items) and external-oriented thinking (EOT; 8 items). In this study, the EOT items were excluded as they were irrelevant to the research question. Participants rated 12 items on a 3-point Likert scale (1 = *not true*, 2 = *always true, 3 = often true*). The total score ranges between 12 and 36. Internal consistency in this study sample was very good (α= .88).

2.3.2. Materials and Measures for Adults

Face dataset: Colourful morphed videos and static images of 18 adult models (young: 3 women M_{age} = 29.8, *SD* = 5.8, and 3 men; M_{age} = 29.9, *SD* = 5.9; middle-aged: 3 women

M_{age} = 50.8 years, *SD* = 5.7, and 3 men; M_{age} = 50.3 years, *SD* = 6; older: 3 women M_{age} = 68.5 years, *SD* = 5.8, and 3 men; M_{age} = 68.9, *SD* = 5.9) were used taken from the Center for Lifespan Psychology, Max Planck Institute for Human Development, Berlin, Germany (Ebner et al., 2010; Holland et al., 2019). The morphed video clips were extended from 2 sec to 10 sec by slowing them down in iMovie software (Apple Inc., 2025). The size of the video clips was 19.5 x 21.5 cm.

Demographic variables: All participants completed a questionnaire to collect socio-demographic variables on age, biological sex, level of education, employment status, relationship status, living condition and ethnicity.

Loneliness: The UCLA Loneliness Scale (Version 3; Russell, 1996) was used to measure participants' loneliness levels. The instrument consists of 20 items (e.g., "*How often do you feel left out*?"). Responses vary on a scale from 1 (*never*) to 4 (*often*) and are scored continuously as the instrument does not provide validated cut-off points. Total scores range from 20 to 80. Internal consistency in this sample was excellent (α= .95).

Depression: The Center for Epidemiologic Studies Short Depression Scale (Ces-D-R-10; Radloff, 1977), a 10-item self-report scale designed to measure depressive symptomatology, was used. Items are rated on a four-point scale (from 0=*rarely or none of the time* to 3=*most or all the time*). Total scores range from 0 to 30, with higher scores representing a more depressed mood. Internal consistency in this sample was very good (α= .87).

Social anxiety: Social Interaction Anxiety-6 (SIAS-6; Peters et al., 2012) was used to measure participants' level of social anxiety regarding initiating and maintaining social connections. The items were measured on a 5-point Likert scale (*from 0=Not at all to*

4=Extremely). Total scores range from 0 to 24 with recommended cut-off score 7 or higher (Zsio et al., 2021). Internal consistency in this sample was very good (α= .87).

Alexithymia: The Toronto Alexithymia Scale (TAS; Bagby et al., 1994) was used to measure alexithymia, a 5-point Likert-type measure (from *1=strongly disagree to 5=strongly agree*) with scores of 52–60 indicating possible alexithymia, and scores above 60 indicating alexithymia. The full scale consists of three dimensions: difficulty identifying feelings (DIF; 7 items), difficulty describing feelings (DDF; 5 items), and external-oriented thinking (EOT; 8 items). In the current study only DIF and DDF dimensions were used, hence, producing a total score range of 12 to 36. Internal consistency in this sample was excellent (α= .93).

2.4. Procedure

The tasks and questionnaires were distributed via a web-based platform Gorilla (www.gorilla.sc) and participants were recruited via SONA, Prolific, and social media (e.g., Facebook, Twitter). After providing their consent and completing demographic questionnaire (Figure 35), participants were then assigned to age-specific facial emotion processing tasks. Participants were presented with a balanced set of facial emotion expressions (Positive: 12 happy; Negative: 6 sad and 6 fear). This balance minimised potential bias from overrepresenting certain emotions, preventing participants from becoming overly sensitive to specific emotions, and maintains ecological validity by reflecting the natural diversity of emotional expressions (Ekman & Friesen, 1971; Gross & Levenson, 1995). It also allowed to reflect the complexity of emotional interactions encountered in everyday social contexts. Before the trials, participants were informed that they would be seeing clips of faces with neutral expressions that gradually morphed

into full emotional expressions. They were instructed to press the spacebar with their left index finger as soon as they detected an emotion (reaction time for sensitivity).

Once they stopped the video, they were asked to indicate whether the emotion was positive or negative (decoding accuracy) by selecting a button (right index finger) using left (Positive) and right (Negative) arrows (Figure 36). They completed 28 trials, including 4 practice trials to ensure a clear understanding of the tasks and 24 test trials. Each trial began with a 250-millisecond fixation cross, followed by a 10-second morphed video clip. Due to software constraints, the order of the blocks was fixed, however, individual trials within each block were automatically randomised by the software. After completing the task, participants were asked to fill out loneliness, depression, social anxiety and alexithymia scales. Participants were then debriefed and reimbursed with either SONA credits, shopping vouchers or Prolific payments.

Figure 35. The Experiment Flow of Experiment 1

2.5. Design

A 2 x 4 x 2 mixed-design ANOVA was conducted to examine the effects of loneliness (2 levels: high-lonely vs low-lonely), age group (4 levels: adolescent, young, middle-age, and older adults), and emotion type (2 levels: positive vs negative) on attentional sensitivity (reaction time on correct responses on emotional stimuli) and decoding accuracy (the percentage of correctly identified facial emotions) respectively. Post-hoc tests with Tukey correction were applied to explore significant main effects and

interactions. Depression, social anxiety, and alexithymia scale scores were included as covariates to control for potential confounding effects.

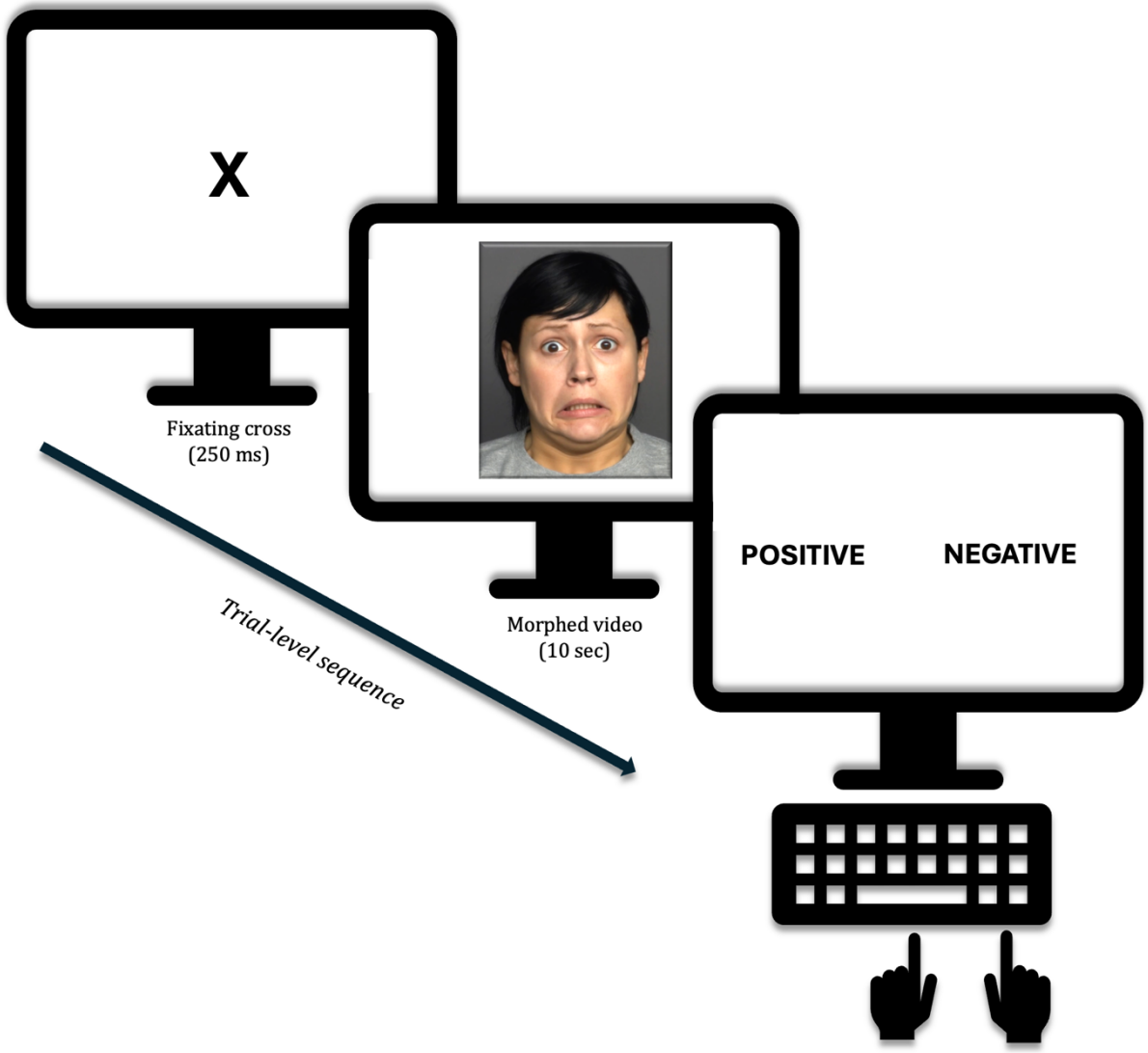


Figure 36. Trial Structure of the Emotion Categorisation Task

Note. Each trial began with a fixation cross (250 ms), followed by a morphed video (10 sec), after which participants categorised the emotion by selecting a valence: Positive or Negative.[6]

[6]*The images used in this thesis were used with a permission granted obtained from the FACES database developed at the Max Planck Institute for Human Development. Permission for their use was granted under the FACES Platform Release Agreement (signed on 9 February 2023). Only images explicitly permitted for research publication and presentation (IDs: 004, 066, 079, 116, 140, and 168) have been included, in line with the release terms.*

2.6. Ethics

This study was approved by the UEA PSY ethics committee (ETH2223-1331). In compliance with open science principles, the study was registered on OSF (https://osf.io/u3vz9/resources). All participants were treated following APA ethical guidelines (American Psychological Association, 2017). Also, the study was conducted in accordance with the principles expressed in the Declaration of Helsinki (World Medical Association, 2013). Moreover, as the research involve human participation, the Research Ethics Code of Practice was followed.

3. Results

3.1. Attentional Sensitivity in Facial Emotion Processing

The analysis revealed a statistically significant interaction between loneliness, emotion and age group, F (3, 355) = 5.119, p = .002, indicating that loneliness influenced attentional sensitivity to emotions in an age-dependent way. The interaction between emotion and age group was also significant, F (3, 355) = 24.86, p < .001, suggesting that different age groups processed facial emotions differently. However, the interaction between loneliness and emotion was not significant, F (1, 355) = 0.073, p = .788.

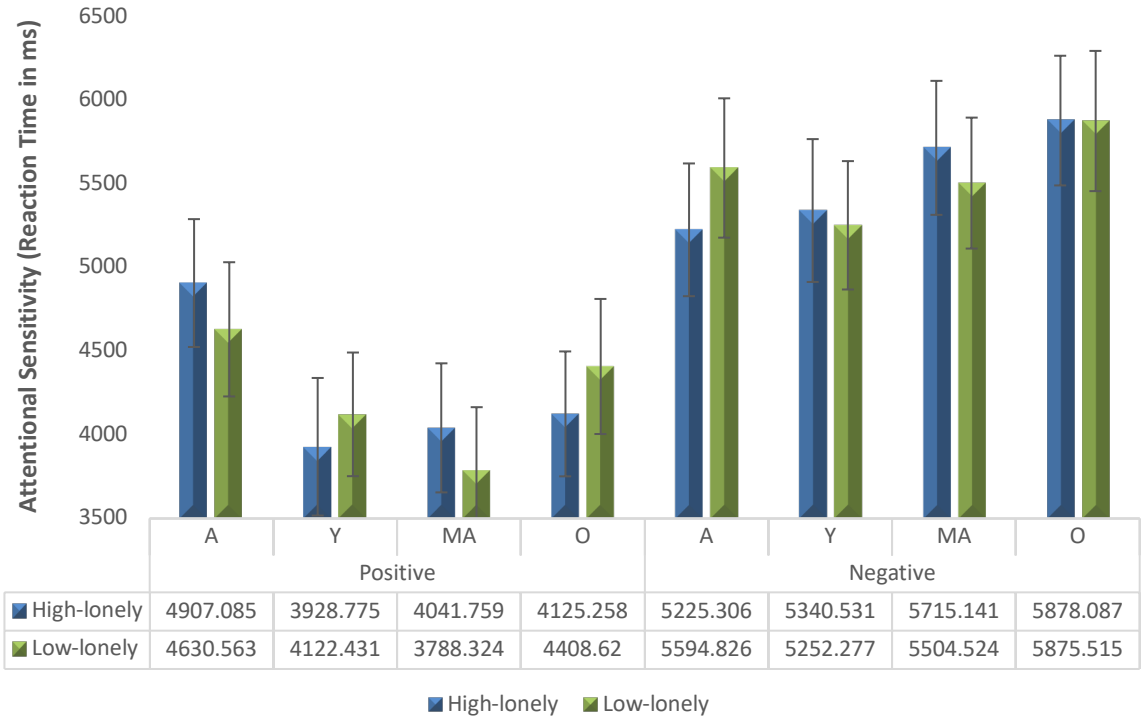
Moreover, the main effect of emotion on attentional sensitivity to facial emotions was also significant, F (1, 355) = 762.52, p < .001, even when controlling for covariates. There was also no significant main effect of loneliness on attentional sensitivity to emotions, F (1, 355) = 0.000, p = .990, indicating that loneliness alone did not influence attentional sensitivity to facial emotions. Meanwhile, a marginal main effect of age

group was found, F (3, 355) = 2.524, p = .057, suggesting a trend towards age-related differences, although it did not reach conventional statistical significance. None of the covariates (depression, social anxiety, or alexithymia) had a statistically significant main effect on attentional sensitivity to emotions (all ps > .05).

Post hoc analyses using Tukey's test were conducted to further examine significant effects (Figure 37). A significant difference was found between positive and negative emotions, t (355) = -27.614, p < .001, with participants being more sensitive (which means faster reaction time on correct responses) for positive emotions than negative ones. Based on the three-way interaction between loneliness, emotion and age group, only one significant difference for positive emotions emerged between high-lonely adolescents and high-lonely young adults, t (355) = 3.56, p = .036, where young adults were more sensitive, decoding positive emotions more quickly and accurately, than adolescents. No other comparisons within positive emotion decoding reached significance after adjustment. For negative emotions, none of the comparisons reached statistical significance after adjustment, as all adjusted p-values were above .05.

Overall, the type of emotion was the most robust factor significantly influencing attentional sensitivity where negative emotions required more time to decode accurately compared to positive emotions for all participants, regardless of loneliness level and age group. While age did not directly influence the attentional sensitivity on its own despite of marginal effect, it moderated the effect of emotion on attentional sensitivity: adolescents and older adults showed reduced attentional sensitivity (slower reaction times for correct responses) to positive emotions, whereas young and middle-aged adult demonstrated increased attentional sensitivity (faster reaction times for correct responses). However, no significant effect of loneliness was found either as a

main effect or in interaction with emotion. That means loneliness alone did not significantly influence how participants processed the facial emotions in terms of attentional sensitivity. Instead, three-way significant interaction was found between loneliness, emotion and age group suggesting that age-related differences in facial emotion processing are influenced by the level of loneliness.



	A	Y	MA	O	A	Y	MA	O
	Positive				Negative			
High-lonely	4907.085	3928.775	4041.759	4125.258	5225.306	5340.531	5715.141	5878.087
Low-lonely	4630.563	4122.431	3788.324	4408.62	5594.826	5252.277	5504.524	5875.515

Figure 37. Mean Attentional Sensitivity Scores (reaction times in ms for correct responses) for Positive and Negative Facial Emotions across age and Loneliness Groups

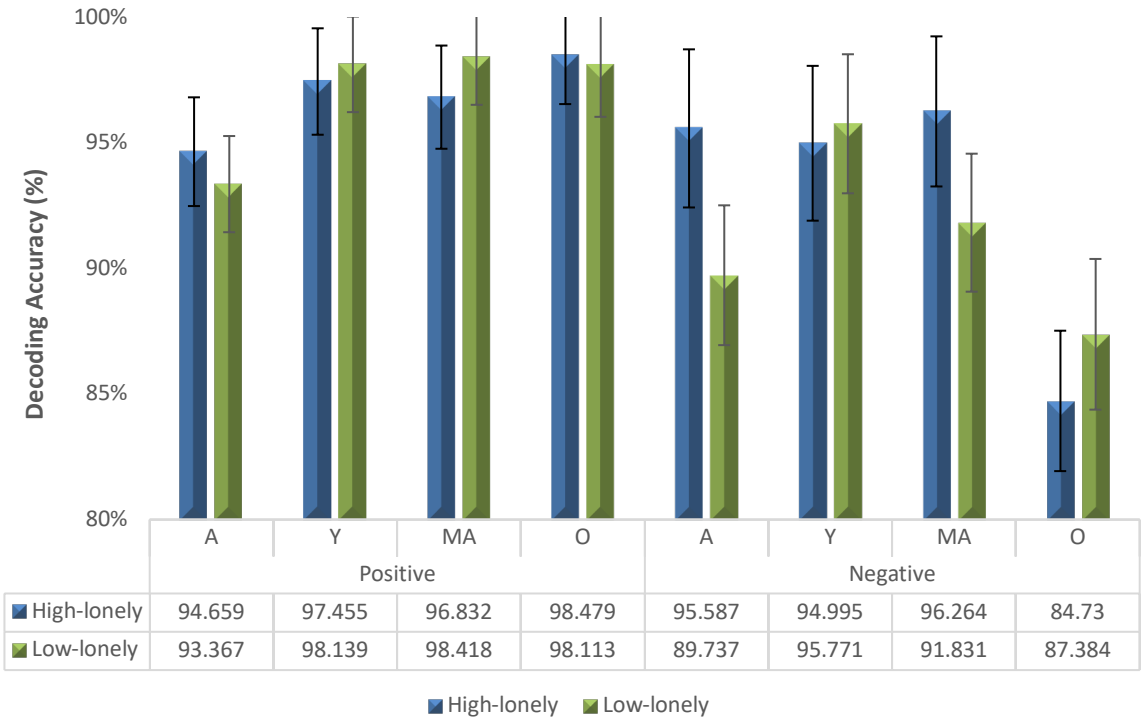
Note. Lower values indicate increased attentional sensitivity, i.e., participants responded more quickly (shorter RTs for correct response). Age groups are coded as: A = Adolescents, Y = Young Adults, MA = Middle-aged Adults, O = Older Adults. Error bars represent 95% confidence intervals.

3.2. Decoding Accuracy in Facial Emotion Processing

The analysis revealed a statistically significant interaction between loneliness, emotion and age group, F (3, 355) = 3.497, p = .016; also, between emotion and age group, F (3, 355) = 17.429, p < .001. Meanwhile, a marginally significant interaction was observed between loneliness and age group, F (3, 355) = 2.611, p = .051. However, the interaction between loneliness and emotion in decoding accuracy was not significant, F (1, 355) = 1.968, p = .162. Moreover, there was no significant main effect of loneliness on decoding accuracy, F (1, 355) = 0.987, p = .321. Yet there was a significant main effect of emotion on decoding accuracy, F (1, 355) = 77.439, p < .001. Moreover, there was a significant interaction between emotion and social anxiety, F (1, 355) = 5.05, p = .025, suggesting that decoding accuracy across emotions varied depending on social anxiety levels.

Post hoc analyses using Tukey's test were conducted to further examine significant effects (Figure 38). Like findings in attentional sensitivity, a significant difference was found between positive and negative emotions, t (355) = 8.800, p < .001, where participants decoded positive emotions more accurately compared to negative ones. According to the three-way interaction between loneliness, emotion and age group, no significant differences emerged for positive emotions across loneliness or age group comparisons, as all p-values exceeded .05. Meanwhile, high-lonely older adults decoded negative emotions significantly less accurately than high-lonely adolescents, t (355) = 5.098, p < .001; young adults, t (355) = 4.803, p < .001; and middle-aged adults, t (355) = 5.522, p < .001. Another interesting significant result was that high lonely older adults were better at decoding positive emotions compared to negative ones, t (355) = 8.716, p < .001.

Overall, like attentional sensitivity, type of emotion was the most robust factor significantly influencing decoding accuracy, potentially a positivity bias. Moreover, age groups moderated the effect of emotion, with older participants demonstrating lower decoding accuracy for negative emotions. While older adults were almost equally good at decoding positive emotions, their accuracy for negative emotions was significantly lower than other age groups. Hence, the overall lower decoding accuracy observed in older adults is not a general deficit in decoding facial emotions but rather a specific reduction in decoding negative facial emotions. Along with this, contradictory to most previous research, loneliness alone did not affect decoding accuracy; it does not interact with emotion significantly either. The interesting significant finding in three-way interaction between loneliness, emotion and age group suggests complex effects.



	A	Y	MA	O	A	Y	MA	O
	Positive				Negative			
High-lonely	94.659	97.455	96.832	98.479	95.587	94.995	96.264	84.73
Low-lonely	93.367	98.139	98.418	98.113	89.737	95.771	91.831	87.384

Figure 38. Decoding Accuracy (%) for Positive and Negative Facial Emotions across Age and Loneliness Groups

Note: Higher values indicate higher accuracy.

4. Discussion

In this experiment, the effect of loneliness, emotion type and age group on attentional sensitivity and decoding accuracy were examined in relation to facial emotion processing while controlling for depression, social anxiety and alexithymia. The findings highlighted the key differences in how different age groups process facial emotions, revealing significant effects of emotion type and age group, while loneliness demonstrated a more complex dynamic interaction with these factors.

The primary finding of this experiment was that, for both attentional sensitivity and decoding accuracy, there was a significant three-way interaction between loneliness, emotion type, and age group. Particularly, emotion type was the strongest predictor of attentional sensitivity. This finding suggests that the relationship between loneliness and facial emotion processing is not linear but influenced by both emotional valence of the stimuli and the participants' age. In other words, loneliness does not have a uniform effect across age groups; rather, its influence on facial emotion processing varies developmentally. The current findings align with previous research, particularly using morphed videos of facial stimuli (Lodder et al., 2016; Vanhalst et al., 2017) in demonstrating no hypervigilance in the high lonely group in terms of attentional sensitivity and decoding accuracy.

Another key finding was a non-linear developmental trajectory in facial emotion processing where attentional sensitivity to positive emotions was decreased among adolescents, increased in young and middle-aged adults, and decreased again in older adults. This non-linear pattern in attentional sensitivity to emotions across ages might be related to developmental changes in lifespan due to ongoing PFC development

(Weiner et al., 2024; Kiesow et al., 2020). This pattern is also consistent with previous research suggesting that neurocognitive changes lead to emotion processing efficiency, which reaches its peak in early-to-mid adulthood before declining in older age (Graham et al., 2024; Qualter et al., 2021).

Finally, reduced decoding accuracy for negative emotions was observed in high-lonely older adults, compared to other age groups. This reflected a positive cognitive bias, in which they decoded positive emotions significantly more accurately compared to negative ones. However, this pattern does not reflect general cognitive decline or impairment, as older adults demonstrated a specific reduction in decoding negative emotion. Instead, it points to selective processing. As proposed by "Socioemotional Selectivity Theory" (Carstensen & Isaacowitz, 1999), motivational shifts in later life lead individuals to prioritise positive cues over negative ones, as people age and perceives their time as limited, they prioritise emotionally meaningful goals and experiences (English & Carstensen, 2014). This dual influence aligns with evidence that emotion processing efficiency peak in early-to-mid adulthood before declining in older age (Graham et al., 2024; Qualter et al., 2021), suggesting that both lifespan motivational changes and cognitive aging shape emotion decoding patterns. For instance, Barber et al. (2015) found that older adults showed a positive bias in attention and memory for emotional faces, even when controlling for cognitive decline. Moreover, cognitive resilience, an ability to adapt to internal and external challenges to sustain mental engagement, (Stine-Morrow & Chui, 2012), might have played in role in older adults by promoting positivity bias (Qualter et al., 2015; Hawkley & Capitanio, 2015). Lastly, neural maturation might have played a role, particularly in brain regions associated with facial emotion processing, such as the PFC and amygdala. This may allow for more efficient,

top-down regulation of emotion perception which enhance the processing of positive emotional information (Kiesow et al., 2020; Pizzio et al., 2022).

Overall, emotion type was the most consistent and robust factor across analyses, where positive emotions were processed faster and more accurately across all participants. While loneliness alone did not directly influence attentional sensitivity or decoding accuracy, age moderated how loneliness and emotion interacted. Specifically, older adults demonstrated a positivity bias, whereas adolescents showed reduced sensitivity to positive emotions.

Some limitations should be considered when interpreting findings from this experiment. Firstly, a cross-sectional design was employed, which prevents drawing a casual conclusion on how loneliness influences facial emotion processing over time. Secondly, while morphed videos provided a dynamic measure of facial emotion processing, they may not fully represent real-world social interactions where additional social cues are involved, such as body movements and voice tone. Lastly, using different scales and face datasets due to developmental and ethical considerations potentially introduced limitations in comparability despite z-score standardisation for scales to address this issue. Thus, future research could explore loneliness in virtual reality (VR) paradigms by replicating real-life situations and multisensory contexts for more ecological validity with a longitudinal approach.

Despite these limitations, this experiment provided crucial aspects of loneliness. As of now, this is the first experiment investigating age group differences allowing developmental perspective and shedding light on age-related changes in cognitive biases in loneliness. Moreover, controlling confounding variables, *depression, social anxiety and alexithymia,* which are highly correlated to loneliness, allowed to see the

specific effects of loneliness. This experiment also included a large sample size (N = 366) across a wide age range (13-83 years) with balanced samples and statistical power. The age-matched faces also minimised the potential own-age biases in facial emotion processing, enhancing the ecological validity of the experiment by reducing any confounding effects. Moreover, the implementation of rigorous data quality check with several steps increased the robustness and reliability of the dataset. A balanced representation of positive and negative emotions also allowed a more comprehensive understanding of how loneliness affects facial emotion processing across valence categories rather than being skewed toward a single emotional dimension.

5. Conclusion

This experiment provided evidence for the complex relationship between loneliness, age and facial emotion processing. The findings challenge the traditional perspective regarding hypervigilance in loneliness by demonstrating that the effects of loneliness on facial emotion processing, in fact, vary across ages. Hence, these findings offer crucial insights into how loneliness interacts with facial emotion processing across ages and emphasises the importance of a developmental viewpoint while also paving the way for the development of age-specific interventions like Cognitive Bias Modification (CBM).

Experiment 2

Interpretation bias towards ambiguous facial emotions across ages in loneliness

Abstract

Interpretation bias, the tendency to interpret ambiguous stimuli in a systematically biased way, is one of the main characteristics of loneliness. Although previous studies have predominantly examined interpretation bias in lonely individuals through scenario-based tasks or clearly valanced facial emotions, little is known about how these biases appear while processing ambiguous facial emotions. Thus, in this experiment, how loneliness and age interact to influence the interpretation of ambiguous and neutral facial expressions have been investigated. A diverse sample of 389 participants, ranging in age from 13 to 83, completed facial emotion perception task with static images that used both neutral faces and faces varying at emotional intensities (25%, 50%, and 75%). The findings suggested that, regardless of loneliness level, misinterpretation of neutral faces, particularly as fear and sad, was significantly higher in adolescents than in other age groups. A three-way interaction (loneliness x age x emotion) was observed at 25% intensity, where high-lonely adolescents demonstrated higher decoding accuracy for both positive and negative emotions compared to all other groups, including their low-lonely peers. At 50% intensity, older adults, especially high-lonely, demonstrated the lowest decoding accuracy across both valences, indicating an age-related decline. At 75% intensity, decoding accuracy remained high across all age groups for both positive and negative emotions, but older adults again demonstrated reduced accuracy for negative emotions. These findings underscore age as a significant predictor of facial emotion perception while identifying a potential for interpretation bias for ambiguous emotional cues in high-lonely adolescents. Overall, the results suggest interpretation bias that depend on both the emotional intensity of facial emotions, the valance, and developmental stage.

1. Introduction

Accurate interpretation of facial emotions is not only important in human survival throughout evolution (Schmidt & Cohn, 2001; Ghaemi-Kerahrodi & Michal, 2020), but it is also vital in maintaining successful social interaction, which is relevant in modern life (Akram et al., 2023). In social life, facial emotions can be inherently ambiguous, requiring interpretation to determine their meaning during interpersonal interactions (Mower et al., 2009; Hassin et al., 2013). For instance, a person with a neutral expression might be perceived as either attentive, considerate, and perhaps even happy, or disinterested, unresponsive, and perhaps even angry, depending on the lens of the observer (Cohen-Chen et al., 2022; Albohn et al., 2019). Interpretation is a semantic process where people construct mental representations that resolve the ambiguity (Blanchette & Richards, 2010; Hirsch et al., 2016). Hence, the facial emotional cues may be open to interpretations leading people to rely on their cognitive mechanisms. The process of interpreting facial emotions is particularly significant in the experience of loneliness and is theorized to be marked by systematic biases known as *interpretation bias*.

Previous research examined the interpretation bias in relation to loneliness with diverse materials, experimental paradigm and techniques yielding mixed results. Up to now, interpretation bias in loneliness has been assessed mostly with ambiguous scenario tasks and findings are well-established demonstrating that lonely individuals are more likely to interpret ambiguous social information as threatening, hostile and rejecting (Nombro et al., 2022; Okruzsek et al., 2021; Lau et al., 2021). Previous empirical research shows that interpretation bias of ambiguous social situations leads to patterns

of social avoidance, and this avoidance subsequently become reinforced as they elicit more negative reactions from other people, which consequently result in vicious cycle of loneliness (Spithoven et al., 2017; Qualter et al., 2015).

However, in terms of interpretation bias in ambiguous facial emotions in loneliness is still limited to only a few studies (Cheeta et al., 2021; Vanhalst et al., 2017: Lodder et al., 2016). As discussed in Chapter 2, the Scoping Review, findings are limited and mixed for children, with only one study (Vanhalst et al., 2017) reporting no bias. In terms of adults, some studies reported increased accuracy for negative facial emotions, such as anger and sad (Lodder et al., 2016; Cheeta et al., 2021), while others found the opposite, decreased accuracy for negative faces (e.g., angry and sad; Smith et al., 2022), or overall lower recognition accuracy for facial emotion recognition (Zysberg, 2012). In contrast, Gardner et al. (2005) reported higher overall accuracy, particularly for low-intensity emotional expressions, suggesting enhanced perceptual sensitivity for ambiguous cues. Moreover, Kanati et al. (2012) found no significant group differences, indicating that loneliness may not universally impact facial emotion interpretation. Importantly, both Cheeta et al. (2021) and Smith et al. (2022) reported interpretation bias, where lonely adults were more likely to misinterpret neutral expressions as negative.

The mixed results across studies investigating facial emotion interpretation in loneliness require the need for further research to better understand the underlying cognitive mechanisms. Therefore, in the Experiment 2, interpretation bias in facial emotion processing with stimuli of varying intensities across ages was investigated in loneliness, leading to the following research questions:

RQ1. Does loneliness influence the misinterpretation of neutral faces across different age groups when controlling for depression, social anxiety, and alexithymia?

RQ2. Are there emotion-specific interpretation biases (e.g., towards happy, fear or sad) in lonely individuals, and do these biases differ by age when controlling for depression, social anxiety, and alexithymia?

RQ3. How do loneliness and age interact to influence decoding accuracy of ambiguous faces at varying levels of emotional intensity (25%, 50%, and 75%) when controlling for depression, social anxiety, and alexithymia?

2. Methods

2.1. Participants

The same participants as in Experiment 1 took part in Experiment 2. As explained in the Experiment 1, 405 participants were allocated into one of four age groups. Following the data quality check based on the current experiment, 17 participants were further excluded based on predefined criteria (see below 2.3.; Figure 39). Final sample consisted of 389 participants. Demographic characteristics of participants and descriptive statistics across age groups (adolescents: 13 – 17 years old; young: 18 – 35 years old; middle age: 36 – 62 years old; older: 63 and over) are presented in Table 19. Percentages are calculated within age groups.

Table 19. Participant Demographics and Descriptive Statistics (*N* = 389)

	Adolescent	Young	Middle age	Older
N	91	98	102	98
Age Mean (+/- SD)	14.69 (1.51)	23.83 (5.77)	46.98 (7.64)	67.87 (4.45)
Sex				
Female	59 (64.8%)	70 (71.4%)	62 (60.7%)	57 (58.2%)
Male	32 (35.2%)	28 (28.6%)	40 (39.3%)	41 (41.8%)
Education level				
Highschool	N/A	52 (60.4%)	30 (29.4%)	41 (42.4%)
Bachelor's degree	N/A	32 (28.6%)	46 (45.1%)	39 (40.2%)
Master's degree	N/A	14 (11%)	14 (13.7%)	12 (10.9%)
PhD	N/A	0	12 (11.8%)	6 (6.5%)
Employment				
Student	91	48 (45.1%)	0	0
Part-time employed	N/A	12 (14.3%)	21 (22.1%)	9 (9.8%)
Full-time employed	N/A	24 (26.4%)	39 (41.1%)	13 (10.9%)
Self-employed	N/A	4 (4.3%)	24 (21.1%)	14 (15.1%)
Homemaker	N/A	0	3 (3.2%)	2 (2.2%)
Retired	N/A	0	12 (6.3%)	60 (62.0%)
Unemployed	N/A	10 (9.9%)	3 (3.2%)	0
Living condition				
Alone	0	16 (16.5%)	11 (10.5%)	21 (20.6%)
With parents	87 (96.5%)	22 (22.0%)	4 (4.2%)	0
With other family members	4 (3.5%)	6 (4.4%)	11 (9.5%)	11 (12.0%)
With friends or shared house	0	35 (37.4%)	2 (3.2%)	1 (1.00%)
With partner/husband/wife	0	19 (19.8%)	74 (72.6%)	65 (67.4%)
Relationship status				
Single	N/A	39 (42.9%)	20 (17.9%)	14 (14.1%)
In a relationship	N/A	46 (47.3%)	18 (18.9%)	10 (8.7%)
Married	N/A	10 (8.8%)	55 (57.9%)	61 (66.3%)
Separated	N/A	3 (1.1%)	4 (2.1%)	6 (3.3%)
Divorced	N/A	0	5 (3.2%)	7 (7.6%)
Ethnicity				
White	71 (78.0%)	62 (63.3%)	83 (81.4%)	97 (99.0%)
Black or Black British - African	4 (4.4%)	14 (14.3%)	10 (9.8%)	0 (0.0%)
Asian or Asian British - Indian	2 (2.2%)	8 (8.2%)	3 (2.9%)	0 (0.0%)
Chinese	3 (3.3%)	3 (3.1%)	4 (3.9%)	0 (0.0%)
Mixed - White and Asian	4 (4.4%)	1 (1.0%)	0 (0.0%)	0 (0.0%)
Arab	2 (2.2%)	4 (4.1%)	0 (0.0%)	0 (0.0%)
Any Other Ethnic Background	5 (5.5%)	6 (6.1%)	1 (1.0%)	1 (1.0%)
Scales				
Loneliness Mean (+/- SD)	13.56 (5.16)	48.46 (11.72)	47.29 (12.71)	40.24 (12.60)
Depression Mean (+/- SD)	8.15 (5.95)	11.98 (6.02)	10.22 (6.41)	7.24 (6.86)
Social Anxiety Mean (+/- SD)	23.13 (7.66)	8.83 (5.06)	5.71 (4.97)	3.33 (3.46)
Alexithymia Mean (+/- SD)	19.41 (6.06)	31.42 (10.48)	26.54 (9.90)	24.43 (8.33)

2.2. Data Quality Check

Below-chance accuracy levels for decoding accuracy measurement were screened and excluded to ensure data quality, following the detailed procedure outlined in the Experiment 2 (Figure 39). Participants who had below-chance accuracy (less than 50%) in valence decoding were excluded from the analysis. This exclusion criteria were only used for the high emotional intensity (75%) condition because facial emotions at this intensity are typically clear and easily recognisable (Young et al., 2002). Therefore, rather than reflecting actual perceptual uncertainty at this level of emotional intensity, below-chance performance likely indicates disengagement, task misunderstanding, or random response (Ratcliff, 1993). However, because of the inherent perceptual ambiguity, responses are likely to vary more among participants for lower intensity and ambiguous emotions (e.g., 50% blends or morphs near the category boundary; Said et al., 2011).

Moreover, outlier removal was not applied to decoding accuracy scores in this dataset to preserve the full range of individual differences in emotion perception. Since this experiment involved inherently ambiguous emotional stimuli, large variability in responses is both expected and theoretically meaningful (Tottenham et al., 2013).

2.3. Materials, Measures and Ethics

As previously stated, Experiment 2 draws from the same original online study as Experiment 1, using the identical participant pool, ethical approval, OSF preregistration, face datasets, questionnaires, and overall experimental infrastructure. However, while the foundational design remains the same, differences in task-specific features, such as the use of static facial images in the Experiment 2 vs dynamic morphs in the Experiment

1, and variations in data quality check led to differences in final sample composition. To avoid redundancy, details of shared materials and procedures are not repeated here unless they differ from those previously described in Experiment 1.

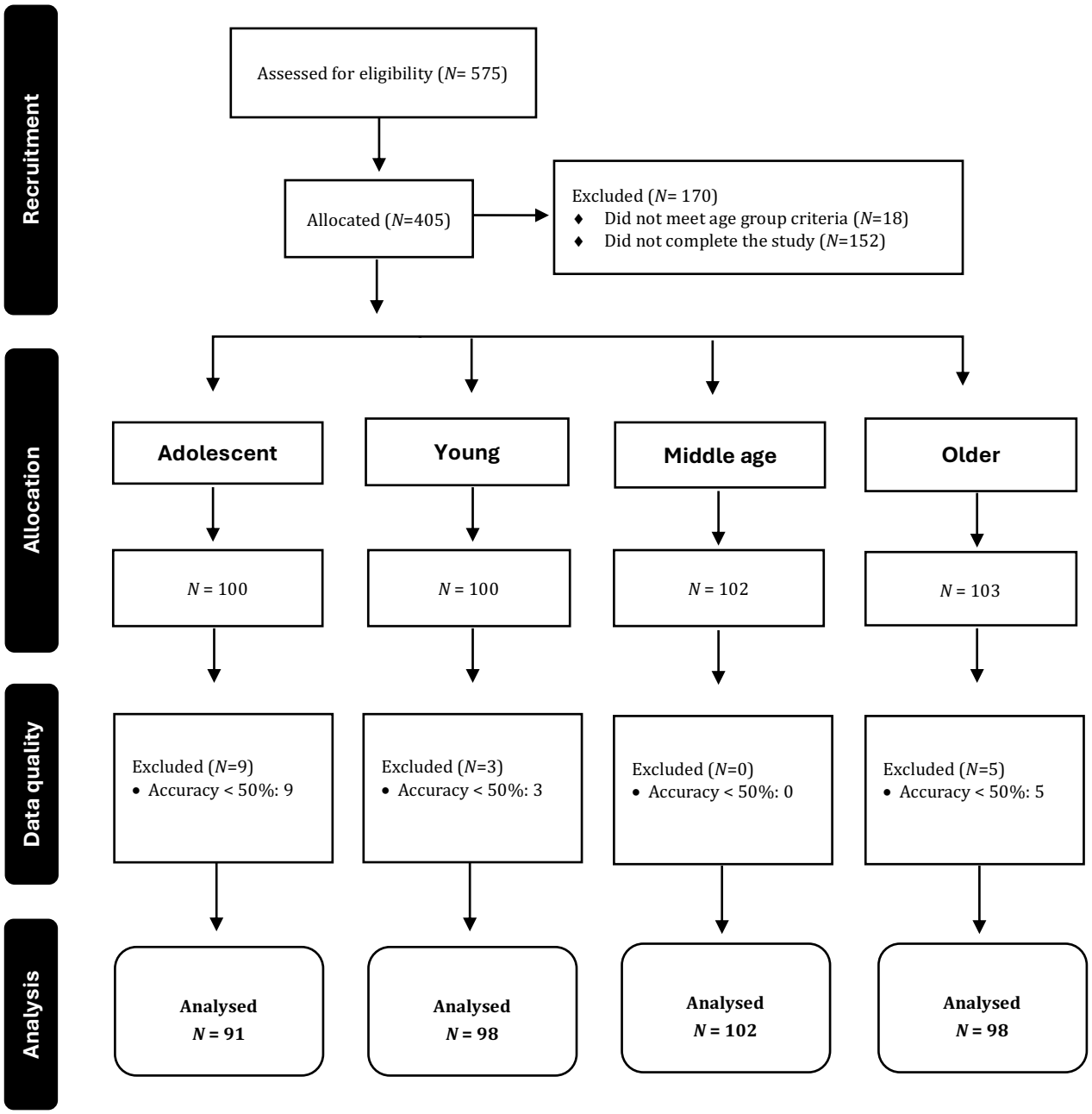


Figure 39. Flowchart Illustrating Participant Recruitment, Allocation and Data Quality Procedures

2.4. Procedure

Participants were presented with 94 trials (4 practice and 90 test trials) with static images displaying four emotions (neutral, happy, sand, fear) across three intensity levels: 25%, 50% and 75% (Table 20 and Figure 40). Before starting, participants completed practice trials to ensure a clear understanding of the task. Each trial began with a 250-millisecond fixation cross, followed by a 400ms static image depicting emotional stimulus with varying emotional intensity (Figure 41 and Figure 43). They selected the perceived emotion as soon as possible Participants selected the emotion using their index finger on the keyboard arrows (left = happy, right = sad, up = neutral, down = fear). This response provided a measure of decoding accuracy, calculated as the proportion of correctly identified emotion types. The four emotions (happy, fear, sad, neutral) were selected to provide a balanced representation of positive and negative valence across varying intensity levels. Due to software constraints, the order of the task blocks was pre-randomised, however, individual trials within each block were automatically randomised by the software. After the task, participants filled out loneliness, depression, social anxiety and alexithymia scales (Figure 42). At the end of the study, participants were debriefed and reimbursed with either SONA credits, shopping vouchers or Prolific payments.

Table 20. Distribution of Facial Emotion Stimuli by Valence, Intensity, and Emotion Type

Intensity	**25%**			**50%**			**75%**		
Valence	**Positive**	**Negative**		**Positive**	**Negative**		**Positive**	**Negative**	
Emotion	Happy	Fear	Sad	Happy	Fear	Sad	Happy	Fear	Sad
Number of stimuli	12	6	6	12	6	6	12	6	6

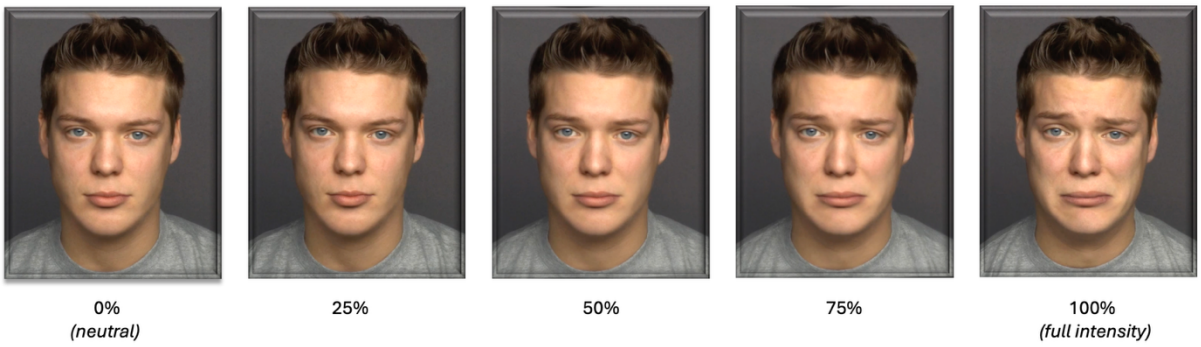


Figure 40. Facial Emotions Intensity Levels in a Morph Sequence

Note: An example of a young adult male actor expressing sad emotion at five intensity levels: 0% (neutral), 25%, 50%, 75%, and 100% (full intensity). Note that 100% emotional intensity has not been included in this experiment to prevent ceiling effects.

Figure 41. Facial Emotion Stimuli Across Age Groups

Note. Examples of facial emotion shown by actors from four different age categories: Adolescent expressing 'Neutral', Young Adult expressing 'Happy', Middle-aged adult expressing 'Fear', and Older Adult expressing 'Sad' emotions.

Figure 42. The Experiment Flow of Experiment 2

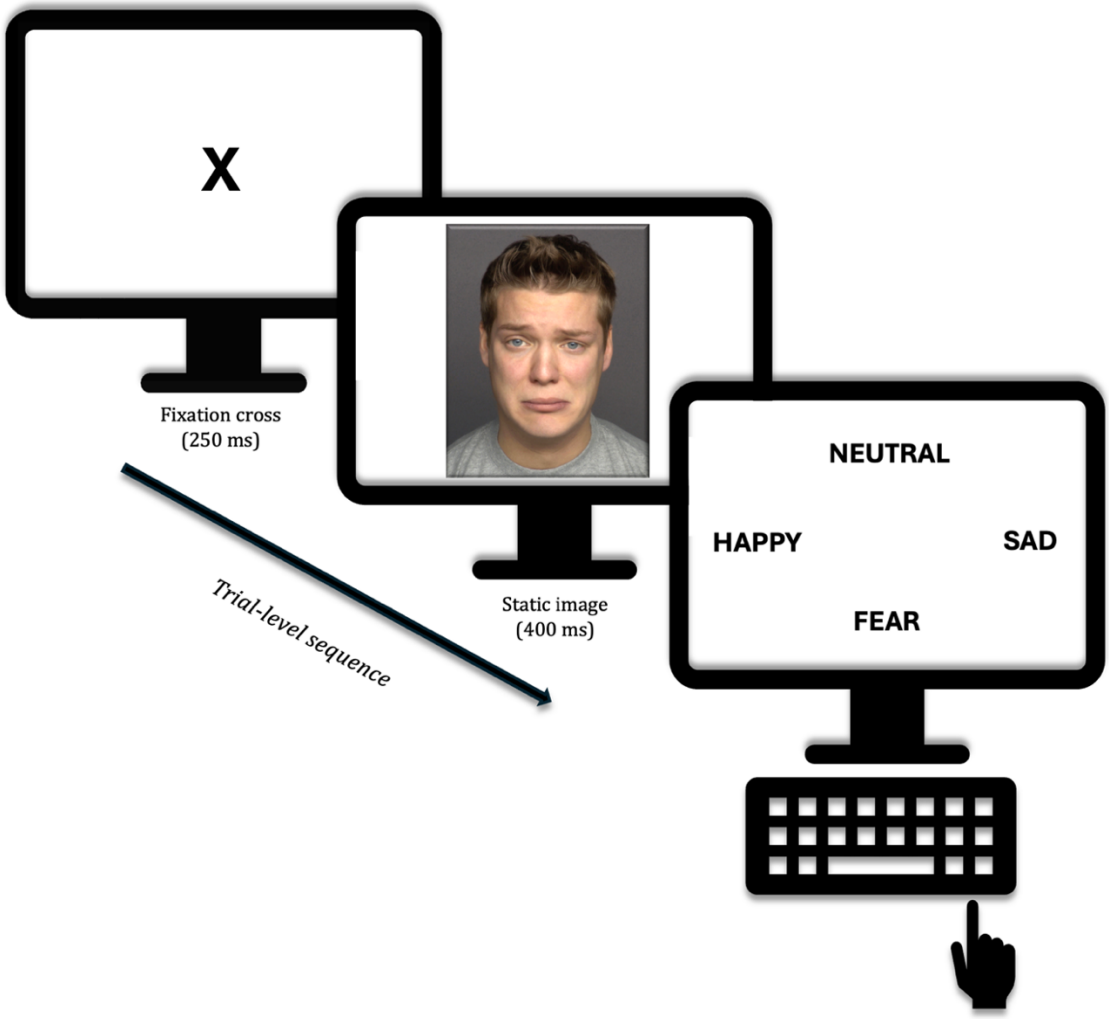


Figure 43. Trial Structure of the Emotion Categorisation Task

Note. Each trial began with a fixation cross (250 ms), followed by a static facial expression (400 ms), after which participants categorised the emotion by selecting from four options: Neutral, Happy, Fear, or Sad.

2.5. Design

A series of factorial and mixed-design ANCOVAs were conducted to examine the effects of emotion type and intensity on decoding accuracy. Emotion (happy, fear, sad, neutral) was treated as the within-subject factor, and emotional intensity (25%, 50%, 75%) was included as a repeated measure where applicable. Post hoc pairwise comparisons with Tukey correction were used to explore significant main effects and interactions. Scores on depression, social anxiety, and alexithymia were entered as covariates to control for individual differences in affective and cognitive processing.

3. Results

3.1. Misinterpretation of Neutral Faces

A factorial ANCOVA was conducted to examine the effect of loneliness and age group on the misinterpretation of neutral faces, while controlling for depression, social anxiety, and alexithymia, indicating that the tendency to misinterpret neutral faces varied by age. There was a significant main effect of age group, F (3, 378) = 46.62, p < .001. However, there was no main effect of loneliness on the misinterpretation of neutral faces, F (1, 378) = 0.15, p = .701, nor a significant interaction between loneliness and age group, F (3, 378) = 0.32, p = .808. None of the covariates were significant (all ps > .12).

Post hoc comparisons using Tukey's HSD revealed significant differences across age groups. Specifically, adolescents, both high- and low-lonely, made significantly more misinterpretation of neutral faces than all other age groups (ps < .001). Misinterpretation rates declined from adolescents through young and middle adulthood, then slightly increased again in older adults. Older adults made significantly more misinterpretations than both young and middle-aged adults (ps ≤ .001), whereas young and middle-aged groups did not differ significantly (p = .42). There were no significant differences between high-lonely and low-lonely participants overall or within any age group (p = .701; Figure 44).

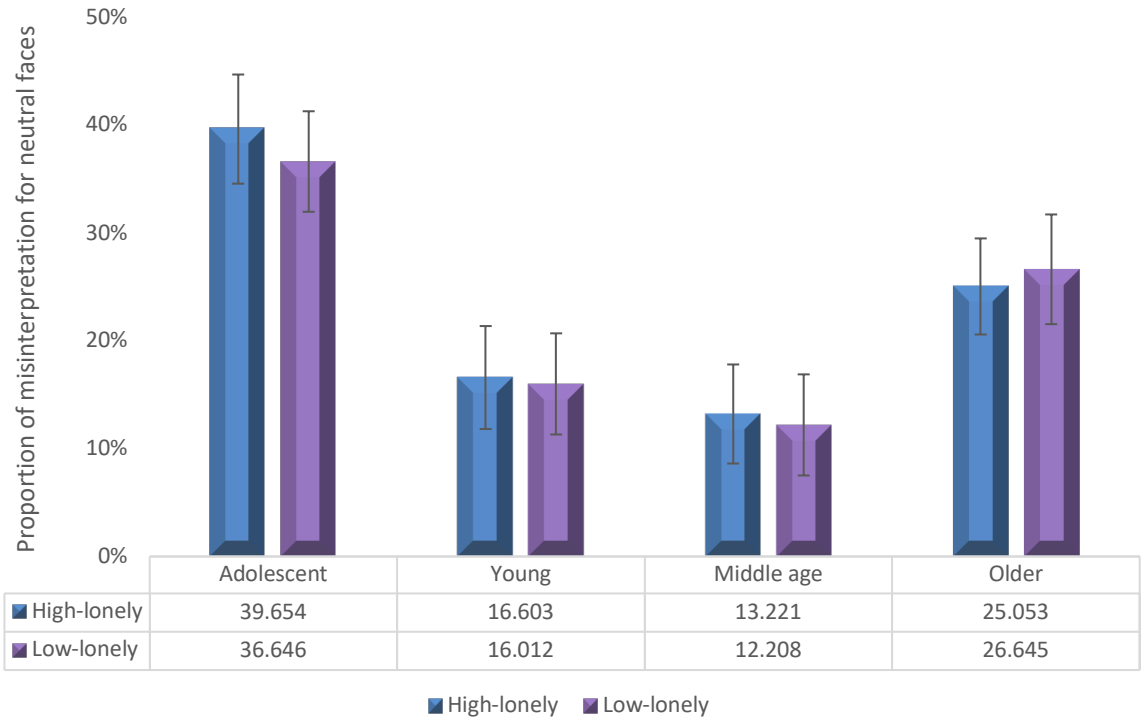


Figure 44. Misinterpretation Rates of Neutral Faces by Age and Loneliness Group

Note. Percentage of incorrect emotion attributions to neutral faces by age group and loneliness level. Error bars represent 95% confidence intervals.

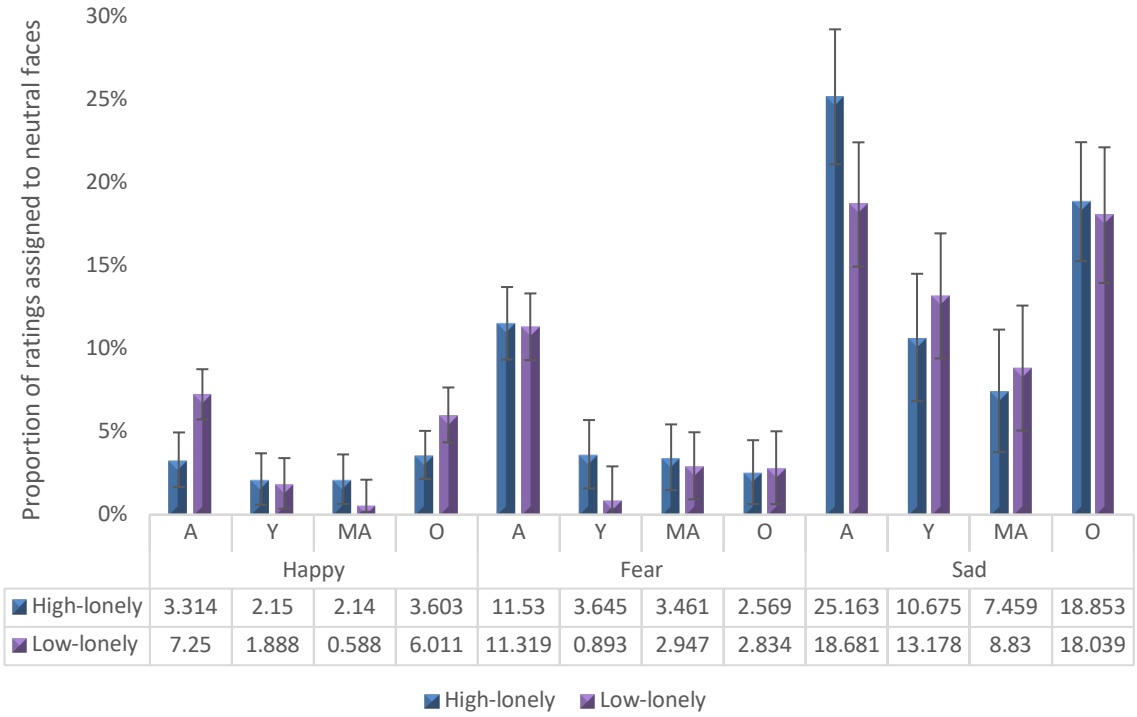
3.2. Emotion-Specific Misinterpretations of Neutral Faces

A 4 x 2 x 3 mixed-design ANOVA was conducted to examine whether the proportion of misinterpretation of neutral faces varied by age groups (4: adolescent, young, middle-aged, older adult), loneliness level (2: high-lonely vs low-lonely), and emotion type (3: happy, fear, sad). Emotion was a within-subjects factor, and loneliness and age group were between-subjects factors. Post-hoc tests with Tukey correction were applied and depression, social anxiety, and alexithymia scale scores were controlled as covariates.

There was a significant a three-way interaction between emotion, loneliness, and age group, F (6, 756) = 3.37, p = .003 as well as a significant interaction between emotion and age group, F (6, 756) = 10.13, p < .001, (Figure 45).

These findings suggest that the proportion of ratings attributed to neutral faces differed not only by age group but also by loneliness level. Moreover, there was a significant main effect of emotion, F (2, 756) = 204.69, p < .001, showing that certain emotions were more likely to be attributed to neutral faces than others. Pairwise comparisons revealed that neutral faces were most often misinterpreted as sad, followed by fear and then happy faces (all *ps* < .001).

Post hoc analyses showed that adolescents significantly misinterpreted neutral faces as sad and fear faces at substantially higher rates than other groups (all *ps* < .001). Particularly, high-lonely adolescents demonstrated more misinterpretations for sad, and fear faces than their low-lonely counterparts (*ps* < .001; Figure 45).



	Happy				Fear				Sad			
	A	Y	MA	O	A	Y	MA	O	A	Y	MA	O
High-lonely	3.314	2.15	2.14	3.603	11.53	3.645	3.461	2.569	25.163	10.675	7.459	18.853
Low-lonely	7.25	1.888	0.588	6.011	11.319	0.893	2.947	2.834	18.681	13.178	8.83	18.039

Figure 45. Misinterpretation Rates of Neutral Faces by Emotion, Age and Loneliness Group

Note: Mean percentage of emotion labels, happy, fear, sad, attributed to neutral faces by age group and loneliness level.

3.3. Decoding Accuracy at 25% Emotional Intensity

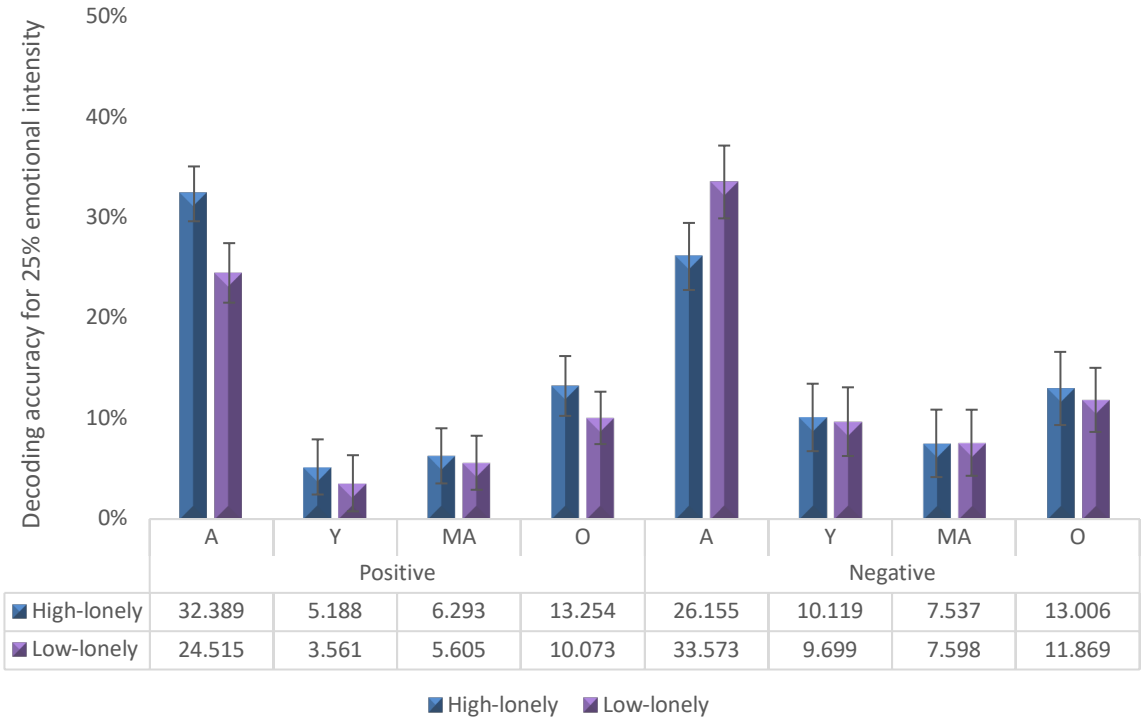
A 4 x 2 x 2 mixed-design ANOVA was conducted to examine the effects of age group (4: adolescent, young, middle-aged, older adults), loneliness level (2: high-lonely vs low-lonely), and emotion type (2: positive vs negative) on decoding accuracy at 25%, 50% and 75% intensities.

The analysis revealed a significant main effect of emotion, F (1, 378) = 9.72, p = .002, suggesting that decoding accuracy for emotions at 25% intensity differed between positive and negative emotions, in which participants decoded positive faces more accurately than negative ones. There was also a significant main effect of age group on decoding accuracy, F (3, 378) = 183.56, p < .001. In contrast, there was no significant main effect of loneliness, F (1, 378) = 1.04, p = .310. Importantly, the interaction between emotion and loneliness was significant, F (1, 378) = 7.16, p = .008, suggesting that the effect of emotion on decoding accuracy varied by loneliness level (Figure 46). Additionally, the three-way interaction between loneliness, emotion and age group was significant, F (3, 378) = 5.13, p = .002, indicating that the combined effects of emotion and loneliness on decoding accuracy further depended on age group. However, the interaction between emotion and age group was not significant, F (3, 378) = 1.76, p =. 154, and the interaction between loneliness and age group was not significant either, F (3, 378) = 0.34, p = .794.

Post hoc comparisons using Tukey's HSD revealed significant differences in decoding ambiguous faces at 25% intensity across age groups and loneliness levels (Figure 46). High-lonely adolescents decoded both positive and negative facial emotions more accurately than all other age groups (ps < .001) and compared to low-lonely

adolescents for only positive emotions (p = .021). Moreover, for positive emotions, high lonely young adults and middle-aged adults decoded faces more accurately than older adults (p = .014, p = .029, respectively). No other comparisons reached significance (all ps >.05).

Overall, high-lonely adolescents demonstrated the highest decoding accuracy for both positive and negative facial emotions at 25% intensity, outperforming all other age groups and even their low-lonely peers but only in recognising positive emotions, not negative. This pattern suggests that adolescents are more attuned to detecting positive cues, even when they are subtle or ambiguous.



	A	Y	MA	O	A	Y	MA	O
	Positive				Negative			
High-lonely	32.389	5.188	6.293	13.254	26.155	10.119	7.537	13.006
Low-lonely	24.515	3.561	5.605	10.073	33.573	9.699	7.598	11.869

Figure 46. Decoding Accuracy for Ambiguous Facial Emotions (25% Intensity) Across Age and Loneliness Groups

Note. Participants' decoding accuracy in identifying positive (left) and negative (right) facial emotions.

3.4. Decoding Accuracy at 50% Emotional Intensity

The analysis revealed a significant main effect of emotion at 50% emotional intensity, F (1, 378) = 266.21, p < .001, indicating that, like 25% emotional intensity, participants decoded positive facial emotions more accurately than negative ones. There was also a significant interaction between emotion and age group, F (3, 378) = 9.89, p < .001, suggesting that differences in decoding accuracy of emotions at 50% intensity between positive and negative emotions varied by age group (Figure 47). The main effect of age group on decoding accuracy was also significant, F (3, 378) = 40.32, p < .001. However, there was no significant interaction between emotion and loneliness, F (1, 378) = 1.80, p = .181, nor was there a significant interaction between loneliness and age group, F (3, 378) = 0.53, p = .659. The three-way interaction significant was not significant either, F (3, 378) = 1.42, p = .236. Moreover, loneliness did not have a significant main effect on decoding accuracy of faces at 50% emotional intensity, F (1, 378) = 0.11, p = .739.

Post hoc comparisons showed that for positive emotions, high-lonely older adults had significantly lower decoding accuracy at 50% emotional intensity compared to high-lonely adolescents (p = .004) and high-lonely middle-aged adults (p < .001), but not high-lonely young adults (p = .398; Figure 47). No corresponding differences were detected among low-lonely participants, with all pairwise comparisons remaining non-significant (all ps > .05). For negative emotions, older adults, both high- and low-lonely, scored significantly lower than all other age groups. Particularly, high-lonely older adults were significantly less accurate than high-lonely adolescents (p = .002), high-lonely young adults (p < .001), and high-lonely middle-aged adults (p = .007). However,

significant differences between high- and low-lonely participants within the same age group were not observed.

Overall, older adults demonstrated significantly lower decoding accuracy for positive and negative emotions at 50% intensity compared to other age groups, except for young adults in positive emotions. Critically, there were no significant differences in accuracy between high-lonely and low-lonely participants within any specific age group. Loneliness did not otherwise show a significant effect on decoding accuracy.

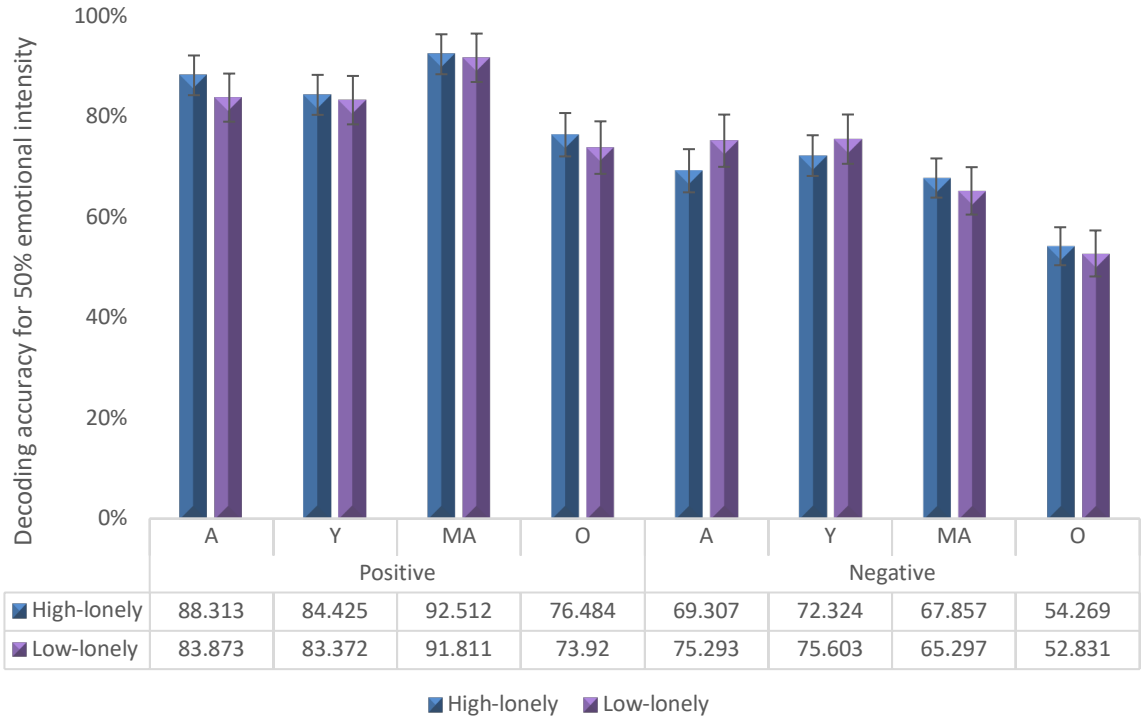


Figure 47. Decoding Accuracy for Ambiguous Facial Emotions (50% Intensity) Across Age and Loneliness Groups

3.5. Decoding Accuracy at 75% Emotional Intensity

The analysis revealed a significant main effect of emotion, F (1, 378) = 295.32, p < .001, indicating that decoding accuracy of emotions at 75% intensity differed

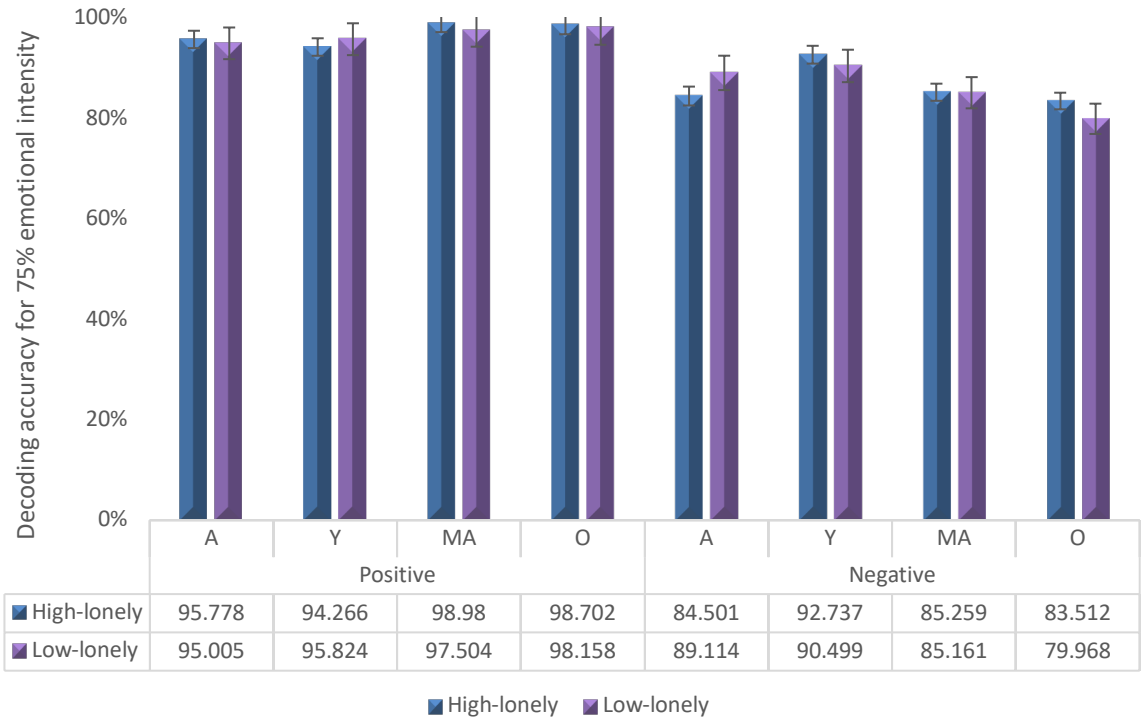
significantly between positive and negative emotions, with higher accuracy for positive emotions, similar to the results in 25% and 50% intensities.

There was a significant interaction between emotion and age groups, F (3, 378) = 18.29, p < .001, suggesting that the effect of emotion type on decoding accuracy varied across age groups (Figure 48). A significant three-way interaction between emotion, age group and loneliness was also found, F (3, 378) = 2.87, p = .037, indicating that the influence of emotion and loneliness on decoding accuracy was further moderated by age group. The results also revealed a significant main effect of age groups, F (3, 378) = 3.57, p = .014. However, the interaction between loneliness and age groups was not significant, F (3, 378) = 1.55, p = .202. The interaction between emotion and loneliness was not statistically significant either, F (1, 378) = 0.00, p = .996. Meanwhile, loneliness did not have a significant main effect on decoding accuracy of emotions at 75% intensity, F (1, 378) = 0.16, p = .690.

Post hoc comparisons using Tukey's HSD showed that participants across all age groups were more accurate in decoding positive than negative emotions at 75% intensity (p < .001; Figure 48). For negative emotions, high-lonely adolescents and high-lonely older adults had significantly lower decoding accuracy compared to high-lonely young adults (p = .033, p = .016, respectively). No other significant differences were found within the adolescent, young adult, or middle-aged groups (ps > .05). Moreover, significant differences between high-lonely and low-lonely individuals within the same age group were not observed for negative faces.

Overall, decoding accuracy improved with increasing emotional intensity, with participants demonstrating consistently higher accuracy for positive than negative emotions across all age groups. Age-related differences were more pronounced for

negative expressions, whereas loneliness did not show a significant effect on decoding performance at high intensity levels.



	Positive				Negative			
	A	Y	MA	O	A	Y	MA	O
High-lonely	95.778	94.266	98.98	98.702	84.501	92.737	85.259	83.512
Low-lonely	95.005	95.824	97.504	98.158	89.114	90.499	85.161	79.968

Figure 48. Decoding Accuracy for Ambiguous Facial Emotions (75% Intensity) Across Age and Loneliness Groups
Note. Participants' accuracy in identifying positive (left) and negative (right) low-intensity emotional expressions)

4. Discussion

In the Experiment 2, the effect of loneliness, emotion type and age groups in misinterpretation of neutral faces and decoding accuracy towards ambiguous faces were examined. The findings partially supported the hypothesis that loneliness is associated with interpretation bias in facial emotion processing and highlighted the robust age-related differences in ambiguous face perception.

The primary finding was that misinterpretation of neutral faces was driven almost entirely by age rather than loneliness. Adolescents, regardless of loneliness level, demonstrated significantly higher misattribution rates, particularly decoding neutral

faces as fear or sad rather than happy faces, than all other age groups. This is consistent with the developmental studies suggesting that adolescents have not yet fully matured in their capacity to decode subtle emotional cues (Blakemore, 2018). A gradual decline in misinterpretation rates through young and middle adulthood was also observed which might reflect improvements in emotion recognition, perspective taking, and social cognitive skills that mature with age (Carstensen et al., 2011). Interestingly, the slight increase in older adults' misinterpretation of neutral faces might be related to declines in perceptual sensitivity (Mather & Carstensen, 2005). The emotion specific analyses further highlighted that sad and fear were the most common misattributions to neutral faces, suggesting negative interpretation bias. Importantly, high-lonely adolescents showed stronger biases with more misinterpretation, perceiving neutral faces as sad and fear, compared to their low-lonely counterparts. This might imply that loneliness may increase threat sensitivity during a developmental stage characterised by heightened emotional reactivity (Del Giacco et al., 2023; Spear, 2009). However, this effect was not observed in adults, suggesting that the influence of loneliness on interpretation biases may be age dependent rather than universal.

At 25% emotional intensity, another remarkable finding emerged, where high-lonely adolescents demonstrated higher decoding accuracy for both positive and negative emotions than all other groups. Furthermore, they had higher decoding accuracy for positive emotions compared low-lonely adolescents. This suggests a possible hypervigilance to emotional cues, potentially reflecting a compensatory mechanism in lonely adolescents which was explained in loneliness loop. According to Evolutionary Theory of Loneliness, loneliness not only lead hypervigilance to negative cues but also motivate them to reconnect with others (Cacioppo et al., 2014). The dual mechanism

could explain why lonely adolescents demonstrated stronger negative interpretation bias by perceiving neutral faces as negative, and higher accuracy for ambiguous faces. Their heightened vigilance towards emotional cues may be an adaptive attempt to recognise social opportunities or threats. However, this hypervigilance may also lead them to misinterpretation and emotional miscalibration due to still-developing prefrontal regulation systems (Del Piero et al., 2016; Vink et al., 2014).

At 50% intensity, older adults, regardless of loneliness level, had significantly lower decoding accuracy for both positive and negative emotions compared to other age groups. This decline was evident across loneliness levels for negative emotions, whereas for positive emotions it was specific to the high-lonely group. This result is aligned with previous research suggesting that processing ambiguous emotional information demonstrate an age-related decline due to neural and cognitive ageing (Ruffman et al., 2008; Isaacowitz et al., 2017). Moreover, loneliness did not significantly affect decoding accuracy at 50% emotional intensity, indicating that ambiguity alone was not sufficient to evoke interpretation bias in lonely individuals outside of a developmental window.

At 75% intensity, where expressions are clearer and less open to misinterpretation, decoding accuracy was generally high across all groups. However, interestingly, high-lonely adolescents and high-lonely older adults still demonstrated lower accuracy for negative emotions compared to high-lonely young adults, suggesting that heightened loneliness may slightly impair recognition of negative cues at both developmental stages but not during adulthood.

In summary, the impacts of loneliness were primarily limited to adolescents, indicating that interpretation bias towards ambiguous facial emotions may be more pronounced during periods of heightened social sensitivity.

5. Conclusion

This experiment contributes to our understand of interpretation bias in loneliness by demonstrating that emotional ambiguity and age significantly influence how facial emotions are interpreted. An age-specific expression of interpretation bias showed that adolescents, particularly high in loneliness, are particularly sensitive to ambiguous emotional cues. In contrast, older adults demonstrated an overall decline in decoding ambiguous faces, particularly negative ones, regardless of loneliness level. These findings highlight the importance of taking developmental stages into account when researching cognitive biases and point to adolescence as a critical time for interventions (e.g., Cognitive Behavioural Modification) aimed at reducing misinterpretations in lonely individuals.

Future research should examine the neural correlates of the interpretation biases towards ambiguous faces and explore whether training interventions could recalibrate interpretation patterns in high-lonely individuals. Moreover, designing longitudinal studies would also provide an understanding on whether these biases contribute casually perpetuating loneliness, or they are an effect or consequences of loneliness. It would also clarify age-related differences in observed biases.

While measuring behavioural reactions in facial emotion processing tasks in online experiments has been crucial, more ecologically valid and controlled environments can be designed as well. For instance, exploring how lonely individuals perceive, interpret, and physically react to facial emotions in real time within immersive Virtual Reality (VR) simulating real-world social interactions could provide more objective and automatic measurements of bodily responses.

Chapter Conclusion

The pilot study and two main experiments in this chapter investigated the role of attention and interpretation biases in facial emotion processing in loneliness across the lifespan, using both dynamic (morphed videos) and static (images with varying emotional intensities) stimuli. Across two experiments, the findings revealed that loneliness-related biases are not uniform but instead interact with age and emotional ambiguity in complex, context dependent ways.

Emotion type was the most robust factor, with positive emotions recognised faster and more accurately than negative ones. Age also emerged as a major moderator: both adolescents and older adults exhibited distinct response patterns. Adolescents, particularly in high-lonely group, demonstrated increased sensitivity to ambiguous faces and more negative misinterpretations, indicating emotional hypervigilance. In contrast, young and middle-aged adults showed peak efficiency in facial emotion processing with higher decoding accuracy. While older adults showed a positivity bias, with reduced accuracy for negative emotions, likely reflecting motivational shifts and cognitive resilience associated with aging rather than loneliness itself. Across all age groups, neutral faces were most frequently misinterpreted as fear or sad, indicating a general negativity bias rather than a loneliness-specific effect.

Overall, loneliness did not consistently influence facial emotion processing, but it interacts with age and ambiguity. Hence, these results highlight a lifespan perspective, and the importance of developmental sensitivity in emotion when examining loneliness.

CHAPTER 5

STUDY 4

Approach-Avoidance Bias Towards Facial Emotions in Loneliness: A Virtual Reality Study

"Between stimulus and response there is a space. In that space is our power to choose our response. In our response lies our growth and our freedom."

Victor Frankl

Chapter Introduction

Facial expressions are among the most immediate and salient social cues, triggering behavioural responses, such as *approach* and *avoidance*, that shape our interactions with others (Frith, 2009). Yet the subtle mechanisms that control how we approach or avoid others, especially in the context of loneliness, remain insufficiently understood. Loneliness, particularly when *chronic*, is associated with a range of cognitive, emotional, and behavioural changes that impact social functioning (Guarnera et al., 2023; Morr et al., 2022a). However, while previous research has focused on mostly attention and interpretation biases, the experiments in this chapter shift the focus towards the *embodied* aspects of emotion: the rapid, automatic, and often unconscious movements of the body that reflect deeper motivational systems. Despite the strong theoretical background, empirical research on Approach-Avoidance Bias (AAB) in loneliness remains sparse, especially in naturalistic and immersive environments (Saporta et al., 2021; Smith & Pollak 2022). Therefore, there is a critical gap between theoretical models and empirical methods. This chapter addresses this gap by leveraging immersive Virtual Reality (VR) technology to simulate realistic social encounters while tracking real-time head movements.

To this end, three interlinked studies were conducted. First, *Experiment 1* was carried out at the Extended Reality (XR) Lab of Radboud University in the Netherlands, using a state-of-the-art VR setup. The goal was to explore how individuals with varying levels of loneliness respond to virtual agents with neutral, happy, and angry facial emotions who approached them in a simulated social scenario. Their embodied responses, such as amplitude and velocity of head movements, were tracked and

analysed as indicators of approach or avoidance motivation. Participants' loneliness level was measured with UCLA Loneliness scale, while depression and social anxiety scales were included as covariates to control for shared variance.

Following this, a *Validation Study* was implemented in preparation for the second VR study, to assess the emotional recognisability of virtual facial stimuli to be used. Since the stimuli were virtual faces, it was essential to ensure that their facial expressions were accurately perceived as intended (e.g., happy, angry, sad). The validation study also provided insight into which emotional categories were prone to misclassification, guiding the exclusion of less reliable stimuli (e.g., fear).

Building upon the findings and methodological insights of the Experiment 1 and the Validation Study, *Experiment 2* was conducted at the VR Lab of University of East Anglia in the UK, with a broader demographic sample, increased sample size, and an expanded range of emotions including sad faces. This experiment also incorporated an additional scale as a covariate, alexithymia, which is highly correlated with loneliness (Qualter et al., 2009).

Collectively, the two VR experiments offer a novel contribution to loneliness research. They apply cutting-edge *Affective Approach-Avoidance VR paradigm* to a research question: *How do lonely individuals behaviourally respond to the others' facial emotions?* The findings presented in this chapter help bridge the gap between cognitive-affective theories and embodied, observable behaviour, showing how the mind and body interact in the context of loneliness.

1. Introduction

The recognition of facial expressions has been one of the most prominent topics in the study of emotions (Souto et al., 2020). Emotions are multifaceted experiences that influence how we think, perceive, and behave (Ali, 2023). Emotional communication is inherently multidimensional and multisensory in nature as emotional information can be derived from various sources including the face, voice, body posture and motion of a person (Heberlein & Atkinson, 2009). Most theories assume that the adaptive advantage of these mechanisms lies in their automaticity ("Automaticity Theory", Schneider & Chein, 2003; "Dual-Process Theory", Tversky & Kahneman, 1974). This refers their spontaneous, fast, and efficient operation that immediately translates evaluations and emotional responses into behaviour (Freeman, 2000). It occurs without relying on time- and resource-consuming deliberate intentions or conscious decision making (Moors & De Houwer, 2006). Particularly, approach-avoidance behaviours could be powerful cognitive-affective mechanisms that allow people to quickly and efficiently avoid unpleasant situations and approach the pleasant ones (Degner et al., 2021). Moreover, approach-avoidance tendencies are considered to operate at a largely automatic and embodied level, translating affective appraisals into motor behaviours with minimal cognitive mediation (Elliot, 2006).

Hence, understanding how individuals respond to emotionally salient social cues is crucial for uncovering the mechanisms that underlie adaptive and maladaptive social functioning. Exploring approach-avoidance dynamics through embodied measures offers a promising pathway for advancing knowledge on emotional regulation, interpersonal behaviours, and social difficulties while studying loneliness. Yet, the role

of embodied emotional processes, particularly how bodily movements reflect internal motivational states, in loneliness remains an emerging field.

1.1. Approach-Avoidance Bias and Embodied Emotional Processing in Loneliness

Approach-Avoidance Bias (AAB) refers to the automatic behavioural tendencies to move towards or away from environmental stimuli based on their emotional valence (Grasso-Cladera et al., 2025). Empirical evidence indicates that human beings are quicker to approach stimuli perceived positive (e.g., rewarding, beneficial, safety, well-being), while they tend to avoid negative stimuli (e.g., threatening, adverse, harmful; Aupperle et al., 2015; Fridland & Wiers, 2018). Consequently, AAB reflects an inherited tendency to automatically engage with stimuli influenced by perceptual, experiential and cognitive biases (Czeszumski et al., 2021). Recent research emphasised the embodied nature of AAB, rooted in its evolutionary role, and underscores the significance of studying it within dynamic and ecologically valid experimental settings. This perspective suggests that physiological mechanisms regulate the automatic behaviours, linking bodily movement with affective decision-making and responses to social cues (Grasso-Cladera et al., 2025). For instance, in a study where they measured approach-avoidance through a joystick task, they found that participants demonstrated quicker congruent responses (approaching positive and avoiding negative) only when bodily movement was involved, suggesting that approach-avoidance tendencies are embodied and movement-dependent (Solzbacher et al., 2022). Hence, emotional valence plays fundamental role in regulating approach-avoidance behaviours which significantly influences interactions in meaningful ways and potentially involve an embodied component (Loijen et al., 2020).

Similarly, the Evolutionary Theory of Loneliness suggests that perceiving motivationally relevant social and emotional cues lead to automatic activation in the appetitive and aversive motivational systems, which fundamentally shapes lonely individuals' behaviours (Cacioppo et al., 2011). Therefore, social alignment and movement synchronisation seems to be reflected at the emotional level such that alignment in motion predicts quality of interpersonal interactions (Kramer et al., 2014; Ramseyer & Tschacher, 2011). Paradoxically, previous research found that as loneliness increases, positive emotional contagion (e.g., love and joy) decreases (Borawski et al., 2021).

While research on approach-avoidance motivations in loneliness is limited, there are a few notable findings which reflect this paradox. For instance, a recent study examined resting parasympathetic nervous system (PNS) activity, measured by heart rate variability (HRV) on a Pavlovian conditioning task with behavioural choice (Smith & Pollak, 2021). They suggested that lonely individuals demonstrate conflicted motivations, showing increased motivation to approach both positive and negative stimuli. Another research conducted three cross-sectional and longitudinal studies using self-report measures, including the Multi-Motive Grid (MMG; Schmalt, 1999), a projective technique using ambiguous pictures and statements to assess hope for affiliation and fear of rejection (Gable, 2006). They found that low-lonely individuals reported stronger approach motivation, whereas high-lonely individuals had increased avoidance motivation. Additionally, another study indicated that lonely individuals demonstrated a stronger motivation for inclusion in group interactions, but only when the effort required to join the group was low, suggesting that desire for inclusion may be inhibited when social engagement demands higher effort (Kanterman & Shamay-

Tsoory, 2022). Together, these studies reflect both between-group differences and within-person ambivalence in how loneliness shape social motivation.

Altogether, these findings indicate that lonely individuals may alternate between approach and avoidance behaviours, depending on the contextual factors. These two motivations seem to be influenced by the duration of the experience of loneliness (situational vs chronic) and social situations (safe vs threatening). For instance, an interesting finding was reported by Saporta et al. (2021) where chronic loneliness was associated with greater avoidance while situational loneliness led to greater approach motivation on a computerised interpersonal distance task. This finding may suggest that situational loneliness may drive people to approach others, whereas chronic loneliness may rather increase avoidance behaviour, which could explain the loneliness paradox, simultaneous feeling of motivation to connect but fear of rejection, proposed by Cacioppo and Hawkley (2009).

1.2. The Role of Amygdala in Embodied Emotional Processing in Loneliness

Carver (1996, *p.360*) noted, *"Although these two tendencies (approach and avoidance) are often layered across each other in the topography of behaviour, they are conceptually distinct from each other. Being distinct, they may be managed by different structures in the nervous system"*. Building on this distinction, Shamay-Tsoory and Kanterman (2024) proposed four systems: (1) gap detection, (2) approach/attraction, (3) avoidance/repulsion, and (4) observation-execution/alignment which support herding behaviours in human beings and are implicated in the experience of loneliness (Figure 49).

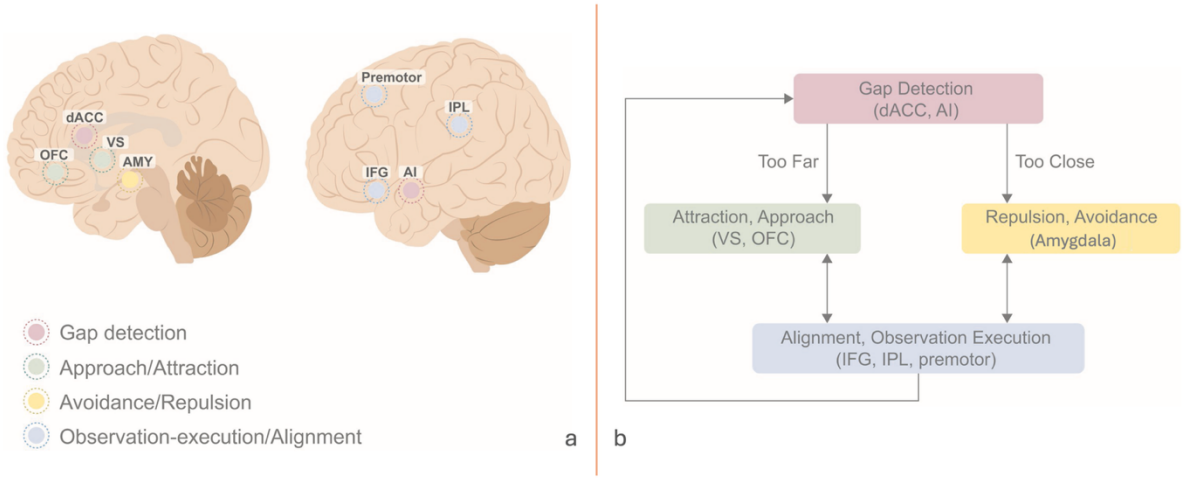


Figure 49. Neural Networks Associated with Loneliness (a) and The Loneliness Cycle Based on the Herding Model (b)

Note: (a) Neutral networks associated with loneliness based on emotional and psychomotor alignment systems underlying herding behaviour, AMY: Amygdala; premotor: premotor cortex. (b) The loneliness cycle based on the proposed neural mechanism for the herding model of loneliness. It is proposed that due to dysregulation in the attraction and repulsion system, and potentially in the gap detection mechanisms too, lonely individuals may have impairment in the ability to accurately assess interpersonal distance and respond appropriately. It would result in a failure to achieve sensorimotor alignment with others (via regions like the premotor cortex, inferior frontal gyrus, and inferior parietal lobule). Consequently, these individuals may struggle to experience meaningful social connection, contributing to the maintenance of loneliness. (retrieved from Shamay-Tsoory & Kanterman, 2024).

In their "Herding Model", *the gap detection system* involves the dorsal anterior cingulate cortex (dACC) and the anterior insula which monitors perceived discrepancies between self and others, playing a central role in evaluating social distance and self-other differences. For instance, Suzuki et al. (2021), found increased dACC and insula activation when participants experienced mismatched visuo-motor feedback from a virtual body, reflecting a neural response to disrupted self-other congruence. Consequently, the hyperactivity within this system has been linked to social exclusion, prediction error, and emotional misalignment. ***The approach/attraction system***, known as Reward Circuitry, encompasses the ventral striatum (VS) and orbitofrontal cortex (OFC), meditates approach motivation and the processing of pleasant social stimuli. This system is important in understanding loneliness, as it is frequently

diminished in chronic loneliness, resulting in decreased social motivation, yet it increases sensitivity to social cues in situational loneliness. In contrast, ***the avoidance/repulsion system*** (the aversive processing) is anchored in the amygdala and supports aversive responses to perceived social threat and might be hyperactive in chronic loneliness contributing to increased avoidance behaviour. Lastly, ***the observation-execution system*** (alignment) which includes the inferior frontal gyrus (IFG), inferior parietal lobule (IPL), and premotor cortex and supports synchrony, imitation, and mimicry, are the core behaviours for social bonding and alignment. They propose that, in loneliness, this system may show hyperactivation, potentially reflecting increased cognitive effort to synchronize or a compensatory mechanism for impaired alignment abilities (Shamay-Tsoory & Kanterman, 2024).

Among these systems, the amygdala emerges as a core component of avoidance and repulsion in loneliness (Shamay-Tsoory & Kanterman, 2024). The amygdala plays a key role in recognising emotions that are highly arousing or ambiguous (Adolphs et al., 2006; Whalen, 1998), and linking facial expressions to emotional meaning, primarily through its interactions with regions like the orbitofrontal and medial prefrontal cortices (Ghashghaei & Barbas, 2002). This process sends the emotional information to both the visual cortex and motor systems, preparing the body to respond (Price, 2003). Beyond initiating autonomic bodily responses, the amygdala also modulates *somatosensory attention* which help people to focus on how their body feel during emotional moments (Damasio, 1996). In essence, the amygdala helps connect what we see, what we feel in our bodies (somatosensory), and how we move or react (motor responses) during emotional experiences (Adolphs & Spezio, 2016).

Thus, the amygdala's role in integrating emotional perception with motor readiness underlies the mechanisms of social synchronisation. Synchronisation in humans might depend on approach and avoidance behaviours, as alignment relies on the optimal distance shaped by attraction and repulsion zones in animals (Shamay-Tsoory & Kanterman, 2024). The affective synchronisation (the embodiment of perceived emotions) is important for better social information exchange between individuals and interpersonal emotion regulation contributing to stronger social bonds (Wood et al., 2021). However, the dysregulated social behaviour system in lonely individuals may result in challenges in attuning to and engaging with others (Cacioppo & Patrick, 2008). In a regulated system, individuals typically observe and assess their social behaviours to be attuned with others, they display synchronised behaviours if a gap is detected in distance or direction between others (Hasson & Frith, 2016).

Despite these theoretical insights, relatively little is known about how loneliness influences the embodied expression of approach-avoidance motivations during social interactions. Traditional cognitive models of loneliness have often emphasised the internal appraisals and self-reported affect (Maitland, 2020; Layden et al., 2018; Johnson et al., 2001; Nurmi et al., 1997; Crick & Ladd, 1993) but have overlooked the bodily and behavioural manifestations of these motivational biases. Therefore, a deeper investigation into how loneliness modulates real-time embodied reactions to emotional stimuli, such as subtle shifts in postural responses in both amplitude and velocity of approach and avoidance behaviours, can provide critical new evidence bridging cognitive-affective theories with observable social behaviour

1.3. Virtual Reality as a Tool to Measure Embodied Emotion in Approach-Avoidance Bias Paradigm

Until recently, emotions were primarily and heavily investigated through passive elicitation methods where participants simply observe stimuli, often neglecting the influence of personal relevance on emotional responses (Somarathna & Mohammadi, 2024). Although the approach-avoidance tasks have become a widely used paradigm for investigating AAB, their variations have primarily been implemented through static computer-based designs which present unrealistic settings (Holleman et al., 2021). Traditional AAB tasks are typically conducted on a computer which include button responses or joystick navigation on the screen providing indirect indicators of avoidance behaviour (Ascone et al., 2023). While these experimental paradigms in AAB research demonstrated evidence and contributed valuable insights, their artificial nature raises concern about the generalisability of findings to real-world social contexts (Degner et al., 2021). Consequently, researchers often faced a dilemma between balancing experimental control with ecological validity. Hence, there has been a growing interest in exploring AAB within more dynamic and naturalistic social contexts.

As a result, VR technology has revolutionised studying emotions and behaviours by offering a unique platform integrating psychology and computer science in more naturalistic yet controlled settings (Binder & Spoormaker, 2020). Current state of the art in the VR technology enables simulation of real-world scenarios with real-time measurements, high immersion, presence and interaction with more nuanced understanding of emotions (Zhang et al., 2023; Chen & Chen, 2023). Particularly, with the broader adoption of VR, objective physiological measurements to automatically assess participant's emotional state are gaining importance. Prior research has

established the feasibility of integrating the AAB study into VR. For instance, Degner et al. (2021) replicated the computer-based paradigm for the AAB in virtual space, which resulted in the replication of the main findings.

Although not all sensorimotor aspects of human behaviour can be entirely replicated in a virtual space, growing evidence supports the validity of studying embodied responses in virtual environments. For instance, Slater and Sanchez-Vives (2016) studied how iVR can reliably replicate human responses and measured brain responses to social cues from robots in an EEG study. They reported that human-like social cues elicited enhances ERP components (e.g., N170, P300) and resulted that there is positive evidence that particularly certain automatic responses occur in virtual environments similar to how they do in the real world (Slater & Sanchez-Vives, 2016).

The VR technology enables researchers to collect comprehensive behavioural data with high precision, including head, eye, hand, and body movements in virtual space beyond traditional metrics like reaction time and response (Phaf et al., 2014; Kenrick & Shiota, 2008; Ascone et al., 2023). Specifically, the measurement of the human body sway (Murugappan et al. 2010), physiological freezing response (Noordewier & van Dijk, 2019), and the speed of body movements (Silvera et al., 2022; Ahuja et al., 2021) are some of the key physiological parameters of human behaviours which allows quantifying real life avoidance behaviour (Murugappan et al., 2010).

Postural sway serves as a non-verbal behavioural indicator that reflects real-time interpersonal interactions in various contexts. In daily life, people rarely sit or stand perfectly still, instead they naturally engage in subtle sway of their head, often unconsciously (Chang et al., 2021). Hence, head movements offer a continuous measure of physical engagement and interpersonal coordination which is less affected by task-

specific movement requirements, such as hand or arm gestures (Shockley et al., 2009). Therefore, head movements, particularly leaning forward and backword, provide a valuable insights into embodied responses to stimuli in the social environment, laying the groundwork for the exploration of emotional and motivational dynamics in loneliness in the studies in this chapter.

2. Experimental Design Rationale and Research Gaps

Despite strong theoretical perspectives in AAB in loneliness, there remains a critical need for empirical, methodological, evidence-based knowledge, particularly using VR. Therefore, we aimed to address these gaps by:

i. Using an immersive VR-based approach to enhance ecological validity.
ii. Measuring continuous, spontaneous head movements as indicators of approach-avoidance behaviour.
iii. Investigating the role of loneliness across different emotional expressions, including neutral stimuli.
iv. Providing an embodied, behavioural test of theoretical models on loneliness and social alignment.

By integrating VR with continuous head movement tracking, the experiments explained below aimed to move beyond traditional metrics like reaction time to capture automatic embodied responses such as amplitude and velocity of head movements during real-life alike social encounter.

Experiment 1

1. Introduction

Experiment 1 was conducted at the Behavioural Science Institute at Radboud University, the Netherlands, as part of an international research collaboration. The VR environment used in this study was developed and provided by the Extended Reality (XR) lab team. The project was supervised by Dr Gero Lange and Professor Mike Rinck, who offered expert guidance on the experimental design and VR integration. Data collection took place at the XR lab, using the institute's advanced VR equipment and facilities[7]. Building on this collaboration and the methodological advances it enabled; the present experiment was designed to address key research questions below concerning how loneliness modulates embodied approach-avoidance responses to emotional social cues in a dynamic virtual environment.

RQ1. Does loneliness influence approach and avoidance biases (embodied postural responses in amplitude and velocity) towards facial emotions (neutral, happy, angry) in a virtual space?

RQ2. How do individual differences in loneliness, depression, and social anxiety (and their interactions) predict variations in embodied approach-avoidance responses towards emotional facial stimuli in a virtual space?

[7] *The VR environment used in this experiment was originally designed and developed by Erik van den Berge, VR Systems Developer at Radboud University, Nijmegen, the Netherlands. His contributions included the creation of the virtual academic conference setting, integration of agent animations, and the calibration of environmental parameters for optimal tracking accuracy and participant immersion. The environment was designed specifically to enable high-fidelity measurement of embodied postural responses, including body sway, and velocity, in a virtual space.*

3. Methods

3.1. Participants

A power analysis was conducted in R software (R Core Team, 2023), using the *pwr* package, to estimate the required sample size based on the effect size reported by Wieser et al. (2010). The significance level was set at 0.05 and the desired power was 0.80. The analysis indicated a required sample size of 55; accordingly, the final sample consisted of 55 participants with a mean age of 23.43 years (*SD* = 3.02; ranging from 18 to 34 years old). Demographic characteristics of participants and descriptive statistics are presented in Table 21.

Table 21. Participant Demographics and Descriptive Statistics (*N* = 55)

Age Mean (+/- SD)	23.34 (3.02)
Sex	
Female	35 (64%)
Male	20 (36%)
Education level	
Highschool	18 (33%)
Bachelor's degree	27 (49%)
Master's degree	10 (18%)
Scales	
Loneliness Mean (+/- SD)	39.69 (9.31)
Depression Mean (+/- SD)	6.52 (4.24)
Social Anxiety Mean (+/- SD)	12.30 (7.63)

3.2. Measures

Demographic variables: All participants completed a questionnaire to collect sociodemographic variables such as biological sex, age, and education level.

Loneliness: The UCLA Loneliness Scale (Version 3; Russell, 1996) was used to measure participants' loneliness level. The instrument consists of 20 items (e.g., *"How often do*

you feel left out?"). Responses vary on a scale from 1 (*never*) to 4 (*often*) and total score ranges from 20 to 80. Internal consistency in this study sample was excellent (α= .90).

Depression: The 8-item Patient Health Questionnaire (PHQ-8; Kroenke et al., 2009) was used that measure depressive symptoms. Participants rated their feelings over the last two weeks on a 4-point Likert scale. The total score ranges from 0 to 32. Internal consistency in this study sample was acceptable (α= .80).

Social anxiety: The 8-item Brief Negative Evaluation Scale (BFNE-S; Leary, 1983) was used to assess social anxiety on a 4-point Likert scale ranging from 0 to 32. Internal consistency in this study sample was excellent (α= .93).

3.3. Materials

Virtual Reality Setup: The experiment was conducted in an XR lab equipped with an HTC Vive Pro Eye head-mounted display (HMD), which provided a resolution of 1440 × 1600 pixels per eye, and a 110° field of view. The HMD included a built-in G-sensor to track head movement across three axes (X, Y, Z) and built-in earphones for audio delivery (Figure 50). It was connected to a desktop computer running Unity, which generated the virtual environment and continuously recorded head position data at ~15 Hz refresh rate using four SteamVR Base Station 2.0 sensors.

Virtual Environment Design and Spatial Layout: The VR environment closely resembled the XR lab space at Radboud University (8.0 × 6.6 m; ~45 m^2 tracking area; Figure 51) and featured white-green chequered flooring, two doors, and conference-style posters

to simulate an academic poster presentation setting. A yellow line on the floor indicated where participants stood in a stationary stance facing the entry doors.

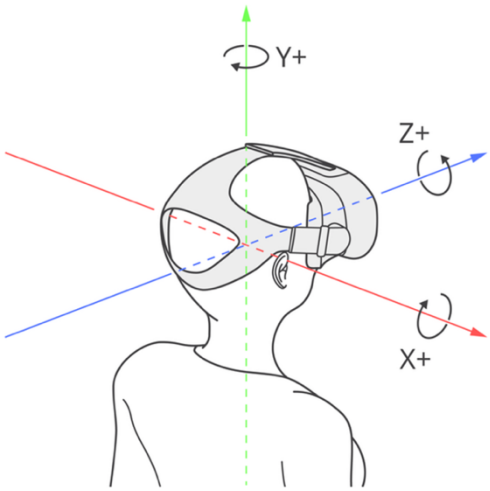


Figure 50. Head-Mounted Display (HMD) Coordinate System and Rotation Axes

Note: This diagram illustrates the coordinate system used by HMD to track head orientation and movement in 3D space. The axes correspond to standard Cartesian coordinates: X+ (Pitch): left and right rotation (e.g., tilting the head) Y+ (Yaw): up and down rotation (e.g., nodding the head) Z+ (Roll): forward and backward rotation (e.g., leaning)

Figure 51. Demonstration of the Virtual Reality Experimental Setup (Radboud University)

Note: The photo was included to depict the VR equipment and lab setup used during the experimental sessions at the XR Lab, Behavioural Science Institute, Radboud University, the Netherlands. It illustrates the motion tracking space and virtual reality headsets used for stimulus delivery and data capture. From left to right: the PhD Researcher (Ceyda Kiyak) testing the task from a participant's perspective; Dr Gero Lange (research lead), Professor Mike Rinck (supervisor), and VR technician Erik van den Berge, who kindly modelled the setup for illustrative purposes with the courtesy and support of the supervisory team.

Virtual Agent Design: Within the Unity software, virtual agents were created using the Morph Character System (http://morph3d.com) expressing different emotions. Only three emotions, *neutral, happy, and angry*, were used in the Experiment 1 (Figure 52). Each avatar's height was adjusted to closely match the participants for a more proportionate interaction using calibration function.

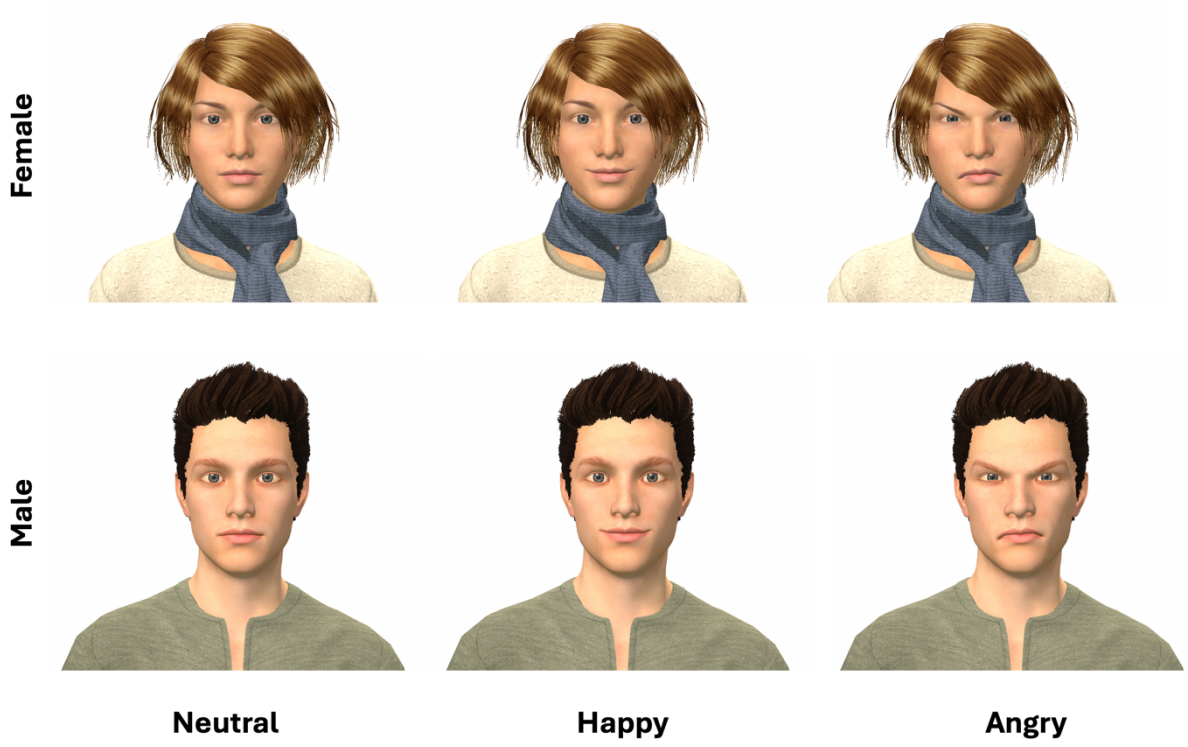


Figure 52. Example Virtual Face across Genders Used in the Approach-Avoidance VR Paradigm (RU Experiment)

3.4. Procedure

Participants were recruited through the university's research participation system (SONA), posters distributed on campus and online advertisement. The experiment involved three phases: Recruitment, *the Affective Approach-Avoidance VR Paradigm* and Post-experiment Measures (Figure 53). In the first phase, upon arrival at the lab, participants received detailed study information and were screened for inclusion (+18 years old) and exclusion criteria (e.g., motion sickness and epilepsy). The nature of VR experiments and potential side effects (e.g., motion sickness) were explained, and written informed consent was obtained.

In the second phase (Figure 54), before beginning the VR task, participants were fitted with a head-mounted display (HMD) and underwent a familiarisation session.

This included calibration of the VR equipment, baseline measurement of postural sway while focusing on a fixation cube, and adjustments for comfort and visual clarity. Participants were given verbal instructions and allowed one minute to familiarise themselves with the virtual environment. They were instructed to stand upright, avoid unnecessary movement, and look straight ahead throughout the task. The VR scenario simulated an academic poster presentation setting and virtual agents served as dynamic emotional stimuli. Each trial lasted around ~20 seconds and followed a three-phase structure: approach, stationary (with emotion exposure), and withdrawal. At the start of each trial (0 seconds), a virtual agent entered the room from 6 meters and began walking towards the participant. During the approach phase (0–5 seconds), the agent moved forward and stopped at a fixed distance of 1 meter. In the stationary phase (5–15 seconds), the agent remained still while displaying one of three facial expressions: neutral, happy, or angry. These emotional expressions were randomly presented across 12 randomised-trials and served as affective stimuli. To ensure participants' focus on the agent's face and promote spontaneous emotional processing, they were instructed to verbally name the virtual agent's eye colour.

During the final withdrawal phase (15–20 seconds), the agent turned around and left the room. Head movement was recorded continuously using the VR system, capturing metrics such as amplitude and velocity of approach and avoidance responses. In the third phase, following the VR task, participants completed a set of self-report questionnaires assessing loneliness, depression and social anxiety levels. Finally, participants were fully debriefed, thanked for their participation, and compensated with either €7.5 or course credit (SONA points).

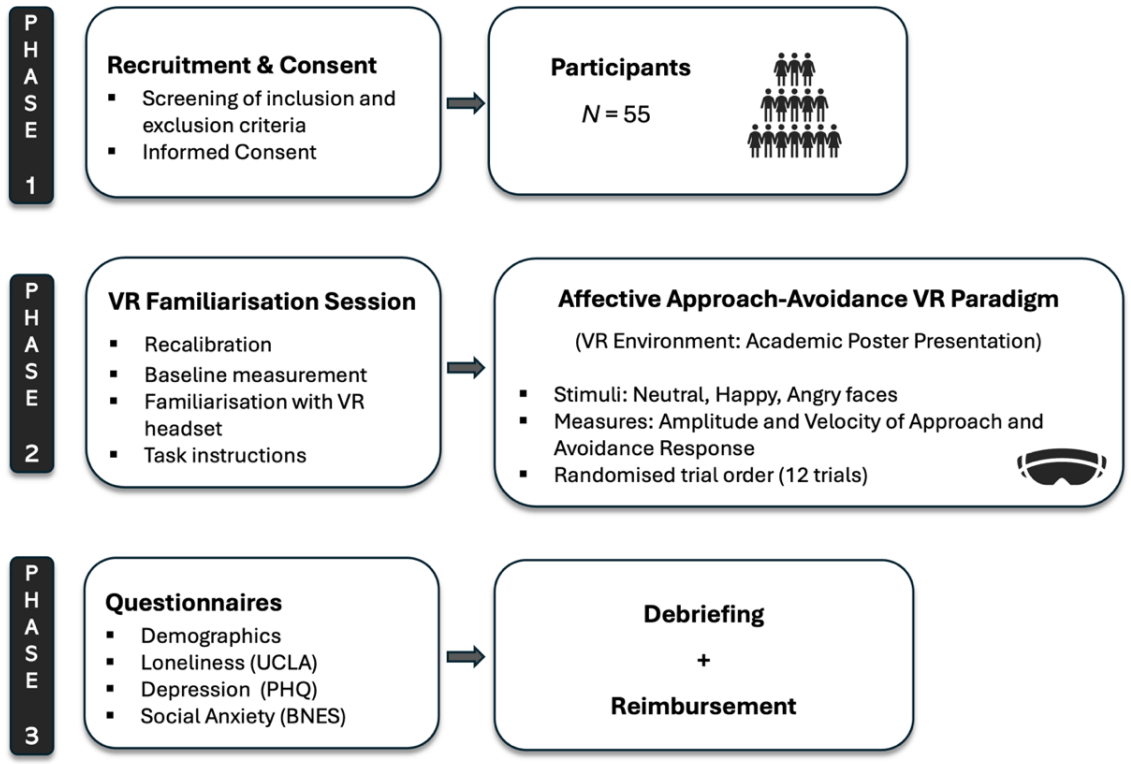


Figure 53. Experiment Flow of the Affective Approach-Avoidance VR Paradigm (RU Experiment)

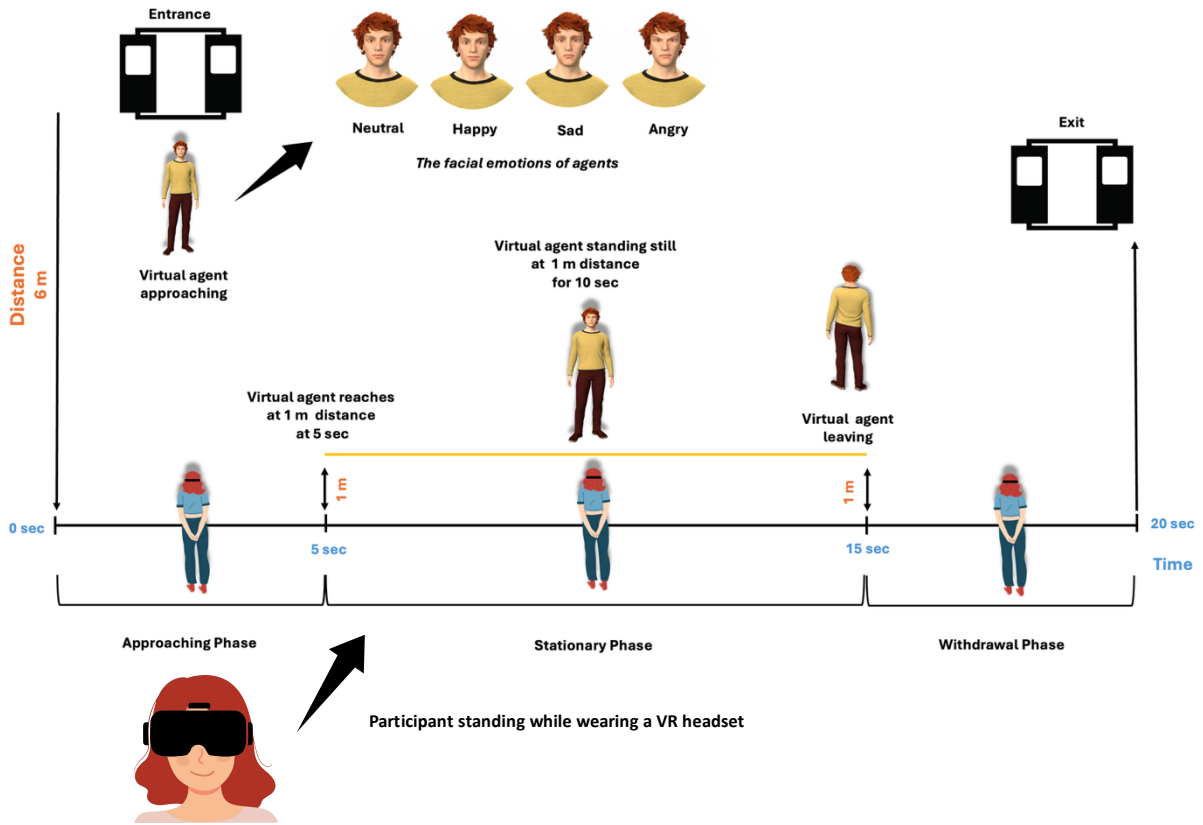


Figure 54. Timeline and Spatial Layout of the Affective Approach-Avoidance VR Trial

3.5. Data Processing

Recent approach-avoidance research in VR suggested that discrete set-based measures introduce measurement errors (e.g., loss of temporal resolution, fixed-point distance measurement), however continuous position tracking may allow investigating automatic behavioural tendencies rather than mere response times (Denger et al., 2021). In line with this suggestion, the body sway of participants was continuously tracked via the head-mounted display's built-in G-sensor, and movements were assessed through each trial to capture subtle automatic behavioural tendencies. Previous studies typically involved selecting a set of key frames from each sample, followed by the extraction and encoding of values from each frame individually (Chen et al., 2024). In line with this approach, representative key frames from the dataset were selected to capture the most relevant temporal snapshots for analysis. These key frames were used to extract frame-level features, which were subsequently processed to identify measures across time such as body sway (leaning forward and backward) and speed allowing for temporal comparisons across conditions.

Body sway (posz) was analysed over time, frame-by-frame, for each 12 trials (Figure 55). This preliminary step was essential for confirming whether the virtual agent's approach and subsequent stop at a fixed interpersonal distance (~1m) reliably evoked measurable embodied reactions. A distinct increase in postural movement was observed across trials around Frame 78, which corresponds to approximately 5 seconds into the trial. This marks the moment when the virtual agent completed its approach and stopped at a 1-meter distance from the participant. From a social-affective neuroscience perspective, 1 meter represents a boundary of interpersonal space that often triggers

heightened autonomic and motor responses (Kennedy et al., 2009; Hayduk, 1983). The body sway peak at this moment suggests a reactive adjustment in postural stability in response to emotional stimuli. Critically, the post-peak decline in sway following the agent's stop may reflect postural stabilisation, a common marker of social vigilance or arousal regulation (Hall et al., 2023). For instance, reduced sway has been linked to increased attentional control and threat monitoring in social contexts (Roelofs et al., 2010). Thus, analysing this specific time window captures the temporal dynamics of embodied social engagement, aligned with the core aims of the study.

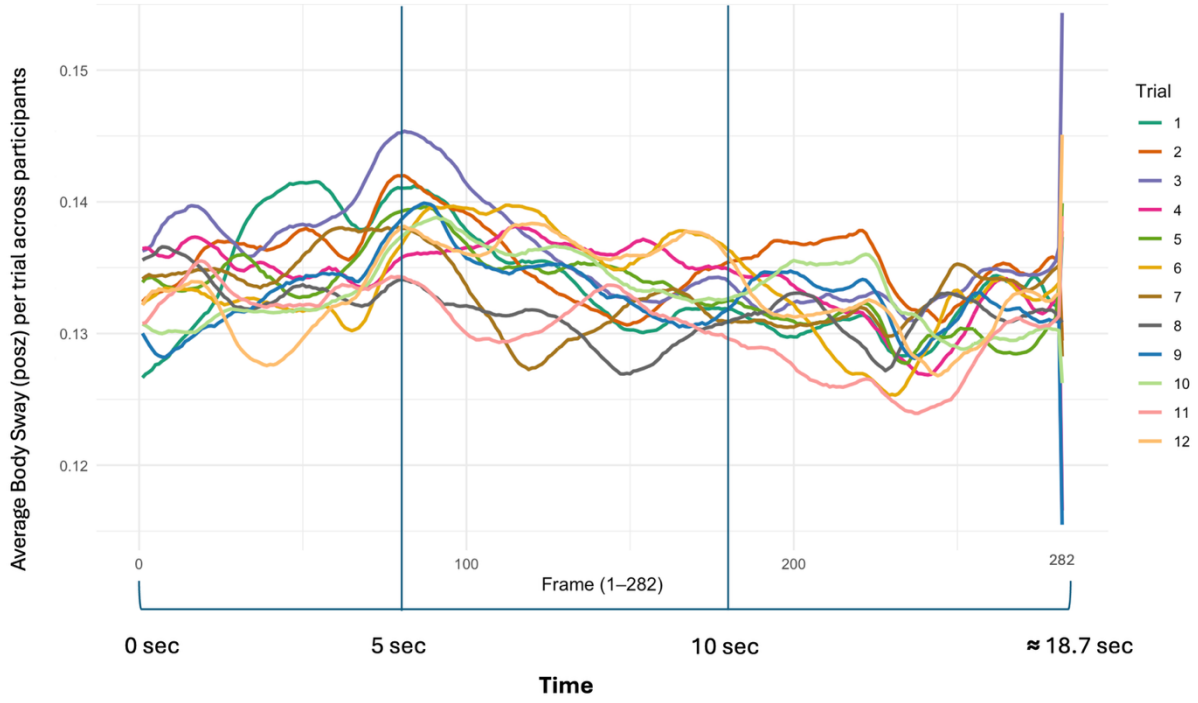


Figure 55. Temporal Dynamics of Body Sway in Response to Virtual Agent Proximity (Trials 1–12; RU Experiment)

Note: Average body sway (posz) across 282 frames (~18.7 seconds) for each of 12 trials, across participants. Vertical blue lines denote timepoints at 0, 5, and 10 seconds. A consistent peak in sway is observed around 5 seconds, the point at which the virtual agent stops at ~1m distance from the participant. This moment appears to elicit a systematic embodied response across trials, suggesting increased postural adjustment. Post-approach, sway levels decrease, indicating possible postural stabilisation.

***Data Source and Structure*:** Body sway data were obtained via VR head-mounted display sensors and analysed at an effective sampling rate of approximately 15 Hz, as

determined from timestamp intervals in the trial-level recordings. The raw data from the HMD consisted of position coordinates pos-x (medio-lateral), pos-y (upward-downward) and pos-z (anterior-posterior) for each second, indicating the position of the HMD in the virtual space. Each row in this dataset corresponds to a single timestamp for a given participant in a specific trial. So, one participant in one trial had approximately 180 rows per trial (12 trials in Experiment 1 and 16 trials in Experiment 2).

Amplitude: In both experiments, each participant completed VR trials in which a virtual agent approached them from a distance of 6 meters to 1 meter while their head position was continuously tracked along the Z-axis (pos-z) to measure forward and backward movement. To quantify participants' physical reactivity to emotional stimuli, movement metrics across trials were computed. First, a *baseline* posture was calculated by averaging the first 30 frames of each trial, capturing the participant's initial stance before the agent approached. The first 30 frames of each trial were selected for baseline because they represent approximately 2 seconds of data, allowing for a consistent measurement of baseline posture before the virtual agent began approaching. Next, leaning forward (*pos-z peak* as an indicative of approach behaviour) was determined by identifying the first frame where the agent was within 1 meter (agent_dist <= 1) and extracting the maximum pos-z value within a 47-frame window surrounding this moment (16 frames before, 31 after). A 47-frame window was selected because it corresponds to approximately 3 seconds of data, providing a standardised time segment to capture participants' immediate motor responses when the virtual agent was closest. Similarly, leaning backward (*pos-z trough* as an indicative of avoidance behaviour) was computed by identifying the minimum pos-z value within the same window. Hence, in

both cases, higher positive values reflect greater movement away from baseline in the respective direction, indicating stronger approach or avoidance responses.

Velocity: Velocity was calculated to quantify embodied approach and avoidance responses by analysing changes in participants' postural position along the z-axis (Pos-Z) during the stationary phase when the agent's distance was fixed at 1 meter. The baseline Pos-Z value and baseline time were recorded at the moment the agent first reached 1 meter. The peak Pos-Z value, representing maximum forward lean, was identified during the stationary phase, and the time to peak was calculated as the difference between the time of peak forward displacement (maximum pos-z) and the baseline time. The trough Pos-Z value, representing maximum backward lean, was also identified during the stationary phase, and the time to trough was calculated as the difference between the time of peak backward (minimum pos-z) displacement and the baseline time. This method captures both the direction and speed of postural movement relative to baseline. Higher positive velocity indicates stronger approach, while more negative velocity indicates stronger avoidance.

Approach and avoidance amplitudes (A) and velocities (V) were calculated using the formulas shown below, based on baseline-corrected Z-axis head-position extrema and their corresponding time points.

$$A_{\text{approach}} = \text{PosZ}_{\text{peak}} - \text{baseline}$$

$$A_{\text{avoidance}} = \text{baseline} - \text{PosZ}_{\text{trough}}$$

$$V_{\text{approach}} = \frac{\text{PosZ}_{\text{peak}} - \text{baseline}}{\text{time}_{\text{peak}} - \text{time}_{\text{baseline}}}$$

$$V_{\text{avoidance}} = \frac{\text{PosZ}_{\text{trough}} - \text{baseline}}{\text{time}_{\text{trough}} - \text{time}_{\text{baseline}}}$$

3.6. Design

A series of linear mixed-effects models (LMMs) were conducted to examine how facial emotion (neutral as the reference condition, happy, angry) as a within-subject factor and loneliness, depression, and social anxiety as continuous between-subject predictors influenced embodied emotional responses, specifically postural indicators of approach and avoidance amplitude and velocity. Facial emotion was treated as a within-subject categorical predictor, while loneliness was entered as a continuous between-subject predictor. Depression and social anxiety were included as covariates in all models to control for their potential confounding influence on approach–avoidance behaviour.

Models were fitted in R (version 4.4.3) using the *lme4* package. Analyses were conducted at the trial level and included a random intercept for participant ID to account for repeated measurements within individuals. Emotion was specified as a fixed effect, and interactions between emotion and loneliness were included to test whether the association between loneliness and embodied responses differed across emotional expressions. Continuous predictors were mean centred prior to analysis to facilitate interpretation of main effects and interaction terms.

To examine whether individuals differed in their sensitivity to loneliness, an alternative model including random slopes for loneliness was tested. Although this model yielded a marginal improvement in overall fit, the estimated random slope variance was near zero and the model exhibited singularity, indicating that individual differences in the effect of loneliness could not be reliably estimated. Consequently, a more parsimonious random-intercept model was retained for all primary analyses.

Degrees of freedom for fixed effects were approximated using the Satterthwaite method implemented in the *lmerTest* package. Omnibus tests of fixed effects and interactions were conducted using Type III analyses of variance within the LMM framework prior to examination of specific parameter estimates. Model fit was evaluated using the restricted maximum likelihood (REML) criterion, residual diagnostics, and marginal and conditional R^2 values.

Post hoc estimated marginal means and pairwise comparisons between emotion conditions were computed using the *emmeans* package, with Tukey adjustments applied to control for multiple comparisons. Simple slopes of loneliness within each emotion condition were examined where relevant. Statistical significance was evaluated at an alpha level of $p < .05$.

Outlier detection was performed separately for each emotion condition using a ±3 SD criterion. Extreme values tended to be emotion-specific (e.g., particularly angry or happy faces). Removing these would have selectively excluded genuine high-amplitude responses tied to specific emotions, potentially biasing the results and underestimating true variability; therefore, all emotion-based extreme values were retained.

3.7. Ethics

Ethical approval was obtained from the institutional ethical committee of Radboud University, prior to the start of the study (ECSW-2019-129). All participants were treated following APA ethical guidelines (American Psychological Association, 2017). Also, the study was conducted in accordance with the principles expressed in the Declaration of Helsinki (World Medical Association, 2013). Moreover, as the research involve human participation, the Research Ethics Code of Practice was followed.

4. Results

4.1. Amplitude of Embodied Postural Responses to Emotional Stimuli

4.1.1. Approach Amplitude Response

Model Overview and Fit: A LMM was used to test whether approach amplitude (how much participants leaned forward towards virtual agents) varied as a function of facial emotion, loneliness, depression, and social anxiety. The fixed effects (predictors) alone explained 7.6% of the variance in approach (*marginal* R^2 = .076), and the model explained 71.9% of the variance when accounting for both fixed and random effects (*conditional* R^2 = .719). The model's REML criterion at convergence was –847.5. The random intercept variance for participants was estimated at 0.00022 (*SD* = 0.0148), and the residual variance was 0.00010 (*SD* = 0.00980).

Omnibus (Type III) ANOVA: A Type III ANOVA using Satterthwaite's approximation revealed that the main effect of emotion on approach amplitude was not statistically significant, F (2, 106) = 1.58, p = .211. The emotion × loneliness interaction approached conventional significance, F (2, 106) = 2.92, p = .059, indicating a trend towards differential associations between loneliness and approach amplitude across emotional expressions, though this effect did not reach the threshold for statistical significance.

Fixed Effects (Coefficient Estimates): According to fixed effect estimates (Table 22), loneliness was not significantly associated with approach amplitude, β = 0.00047, *SE* = 0.00030, t (71.5) = 1.60, p = .115. Depression and social anxiety were not significantly associated with approach amplitude either (both ps > .15).

Table 22. Fixed Effect Estimates from the Linear Mixed Effects Model Predicting Approach Amplitude (RU Experiment)

Predictor	Estimate (β)	SE	df	t	95% CI (Lower, Upper)	p
Intercept: Neutral	0.01136	0.00240	77.8	4.74	[0.0066, 0.0161]	**< .001*****
Angry vs Neutral	0.00328	0.00187	106	1.76	[−0.0004, 0.0069]	.082†
Happy vs Neutral	0.00119	0.00187	106	0.64	[−0.0025, 0.0049]	.527
Loneliness	0.00047	0.00030	71.5	1.60	[−0.00012, 0.00106]	.115
Depression	0.00062	0.00053	51.0	1.17	[−0.00044, 0.00168]	.247
Social Anxiety	−0.00048	0.00033	51.0	−1.43	[−0.00115, 0.00019]	.158
Angry ✻ Loneliness	0.00011	0.00021	106	0.51	[−0.00030, 0.00052]	.611
Happy ✻ Loneliness	−0.00037	0.00021	106	−1.79	[−0.00078, 0.00004]	.077†

Note: The reference level for emotion is neutral. A random intercept for participant ID was included. All continuous predictors were mean centred prior to analysis. CI = Confidence Interval. † indicates effects that approach statistical significance (p > .05) but do not meet the conventional threshold for significance (p < .05) and should be interpreted cautiously.

Estimated Marginal Means: Estimated marginal means showed that approach amplitude was highest for angry emotion (M = 0.0146, SE = 0.0024), followed by happy emotion (M = 0.0125, SE = 0.0024), and lowest for neutral emotion (M = 0.0114, SE = 0.0024).

Loneliness Slopes and Pairwise Comparisons: Simple slope analyses indicated positive, but non-significant, associations between loneliness and approach amplitude across all emotional conditions. The largest slope was observed for angry expressions (β = 0.00058, SE = 0.00030), followed by neutral (β = 0.00047, SE = 0.00030) and happy expressions (β = 0.00010, SE = 0.00030). None of these slopes reached statistical significance, and all corresponding confidence intervals included zero. Exploratory Tukey-adjusted pairwise comparisons of loneliness slopes between emotional conditions (Table 23) revealed no significant differences between any emotion pairs (all $ps \geq .178$). Although the difference in slopes between angry and happy expressions approached significance, β = 0.00048, SE = 0.00021, t (106) = 2.30, p = .060.

Table 23. Pairwise Comparisons of Loneliness Slopes by Emotion for Approach Amplitude (RU Experiment)

Contrast	Estimate (B)	SE	df	t	95% CI (Lower, Upper)	*p*
Neutral vs Happy	0.00037	0.00021	106	1.79	[−0.00017, 0.00077]	.178
Neutral vs Angry	−0.00011	0.00021	106	−0.51	[−0.00057, 0.00037]	.867
Happy vs Angry	−0.00048	0.00021	106	−2.30	[−0.00087, 0.00007]	.060†

Note. Pairwise comparisons assess whether the predictive slopes of loneliness on approach amplitude differ between emotional conditions. p-values were adjusted using Tukey's method.

Overall, these results indicate that approach amplitude responses to happy faces remained relatively stable, showing little change in leaning forward as loneliness level increases. In contrast, approach responses to angry and neutral faces showed a more pronounced increased trend as loneliness increased, however these effects were not statistically significant (Figure 56).

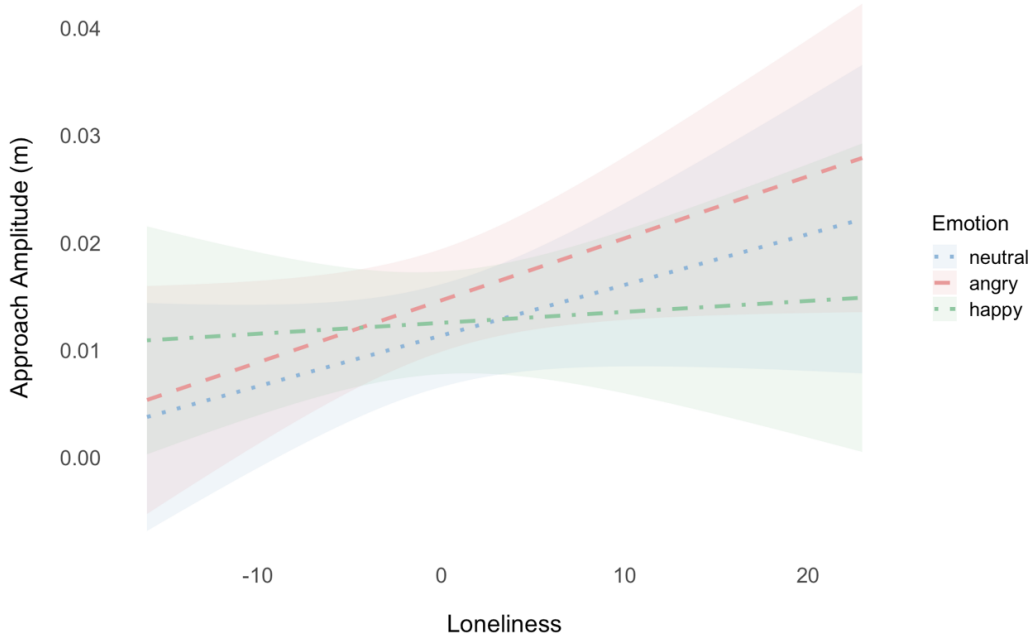


Figure 56. Interaction Between Loneliness and Emotion on Approach Amplitude Response (RU Experiment)

Note: The figure illustrates predicted approach amplitude (y-axis) as a function of loneliness (x-axis), with separate lines for each facial emotion condition (neutral, happy, angry). Predictions are derived from the fixed effects of the linear mixed-effects model, with shaded areas representing 95% confidence intervals. Emotion was dummy coded with neutral as the reference condition. Higher approach amplitude reflects greater leaning forward movement in response to emotional facial stimuli, interpreted as a proxy for automatic approach tendency.

4.1.2. Avoidance Amplitude Response

Model Overview and Fit: An LMM was conducted to investigate whether avoidance-related embodied postural responses varied as a function of facial emotion, loneliness, depression, social anxiety and their interaction. The model explained 7.3% of the variance in avoidance amplitude through fixed effects alone (*marginal* R^2 = .073), and 36.8% when accounting for both fixed and random effects (*conditional* R^2 = .368), suggesting that although individual differences contributed meaningfully to avoidance amplitude, a substantial proportion of variance was attributable to within-participant fluctuations across trials. The model's REML criterion at convergence was –972.8. The random intercept variance for participants was estimated at 0.00003 (*SD* = 0.00545), and the residual variance was 0.00006 (*SD* = 0.00798).

Omnibus (Type III) ANOVA: A Type III ANOVA using Satterthwaite's approximation revealed that the main effect of emotion on avoidance amplitude was not statistically significant, F (2, 106) = 1.26, p = .287. However, the interaction between emotion and loneliness was statistically significant, F (2, 106) = 3.49, p = .034, indicating that the association between loneliness and avoidance amplitude differed across emotional expressions.

Fixed Effects (Coefficient Estimates): According to fixed effect estimates (Table 24), loneliness was significantly negatively associated with avoidance amplitude, β = –0.00033, *SE* = 0.00016, t (114.6) = –2.11, p = .037, suggesting reduced backward movement with increasing loneliness at the reference emotion. Depression and social anxiety were not significantly associated with avoidance amplitude (*ps* > .70).

Table 24. Fixed Effect Estimates from the Linear Mixed Effects Model Predicting Avoidance Amplitude (RU Experiment)

Predictor	Estimate (β)	SE	df	*t*	95% CI (Lower, Upper)	*p*
Intercept: Neutral	0.00892	0.00130	128.5	6.85	[0.00635, 0.01150]	**< .001*****
Angry vs Neutral	−0.00233	0.00152	106	−1.53	[−0.00533, 0.00066]	.128
Happy vs Neutral	−0.00062	0.00152	106	−0.41	[−0.00362, 0.00238]	.683
Loneliness	−0.00033	0.00016	114.6	−2.11	[−0.00064, −0.00002]	**.037***
Depression	−0.00008	0.00024	51	−0.35	[−0.00056, 0.00040]	.728
Social Anxiety	0.00006	0.00015	51	0.39	[−0.00024, 0.00036]	.702
Angry ✻ Loneliness	−0.00003	0.00017	106	−0.17	[−0.00036, 0.00030]	.864
Happy ✻ Loneliness	0.00037	0.00017	106	2.20	[0.00004, 0.00070]	**.030***

Note. The reference level for emotion is neutral. All continuous predictors were mean-centred.

Estimated Marginal Means: Estimated marginal means indicated that avoidance amplitude was highest for neutral (M = 0.00892, SE = 0.00130), followed by happy (M = 0.00830, SE = 0.00130) and angry expressions (M = 0.00659, SE = 0.00130).

Loneliness Slopes and Pairwise Comparisons: Simple slope analyses showed that loneliness was significantly negatively associated with avoidance amplitude for neutral faces, β = −0.00033, SE = 0.00016, and for angry faces, β = −0.00036, SE = 0.00016, indicating reduced avoidance responses with increasing loneliness in these conditions. In contrast, the slope for happy faces was not significantly different from zero, β = 0.00004, SE = 0.00016. Exploratory Tukey-adjusted pairwise comparisons of loneliness slopes between emotional conditions (Table 25) indicated no significant differences between any emotion pairs following correction for multiple comparisons (all $ps \geq .051$). Although the difference between angry and happy slopes approached statistical significance, β = −0.00040, SE = 0.00017, t (106) = −2.37, p = .051, this effect did not remain significant after correction and should be interpreted cautiously in light of the omnibus interaction.

Table 25. Pairwise Comparisons of Loneliness Slopes by Emotion for Avoidance Amplitude (RU Experiment)

Contrast	Estimate (B)	SE	df	*t*	95% CI (Lower, Upper)	*p*
Neutral vs Angry	0.00003	0.00017	106	0.17	[−0.00057, 0.00037]	.984
Neutral vs Happy	−0.00037	0.00017	106	−2.20	[−0.00017, 0.00077]	.076†
Angry vs Happy	−0.00040	0.00017	106	−2.37	[−0.00087, 0.00007]	.051†

Note. p-values were adjusted using Tukey's method to control for multiple comparisons. Degrees of freedom were estimated using the Kenward–Roger approximation.

Overall, higher level of loneliness was significantly associated with reduced avoidance responses to neutral and angry faces, whereas avoidance responses to happy faces remained relatively stable across levels of loneliness (Figure 57). In contrast to approach amplitude, avoidance behaviour showed clearer evidence of emotion-specific modulation by loneliness, suggesting that loneliness may differentially influence withdrawal-related embodied responses depending on the facial emotion.

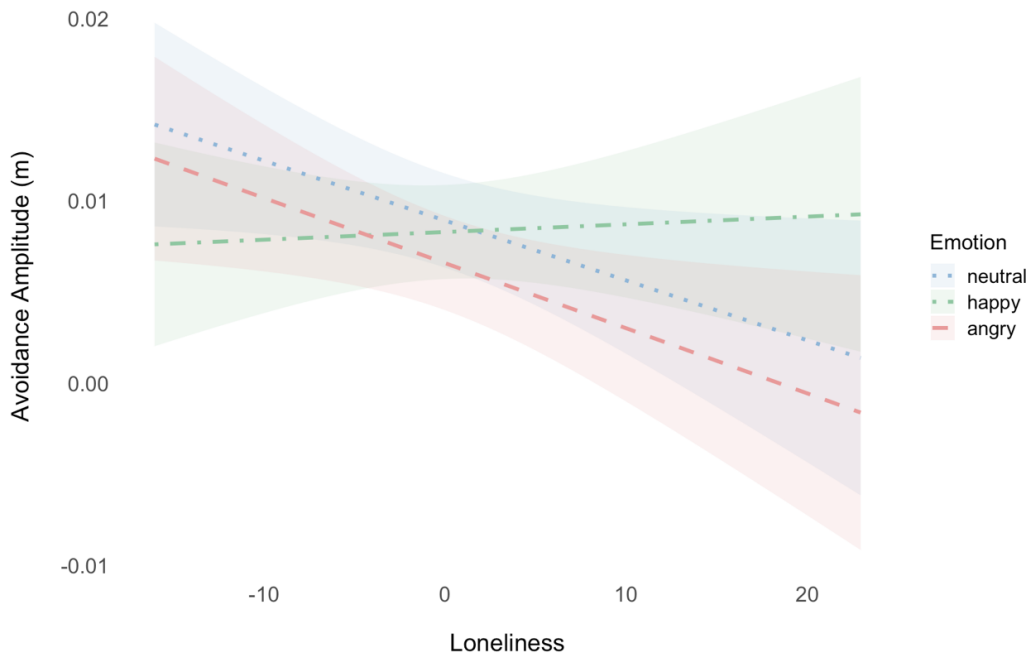


Figure 57. Interaction Between Loneliness and Emotion on Avoidance Amplitude Responses (RU Experiment)

Note. Loneliness was mean-centred. Avoidance amplitude is reported in meters (m), with higher values stronger avoidance amplitude responses to the emotional stimuli.

4.2. Velocity of Embodied Postural Responses to Emotional Stimuli

4.2.1. Approach Velocity Response

Model Overview and Fit: LMM was conducted to examine whether approach-related velocity varied as a function of facial emotion, loneliness, depression, and social anxiety. The model explained 3.2% of the variance in approach velocity through fixed effects alone (*marginal* R^2 = .032), and 58.7% when accounting for both fixed and random effects (*conditional* R^2 = .587). The model's REML criterion at convergence was –1033.2. The random intercept variance for participants was estimated at 0.00005 (*SD* = 0.00676), and the residual variance was 0.00003 (*SD* = 0.00584).

Omnibus (Type III) ANOVA: A Type III analysis of variance using Satterthwaite's method indicated that the main effect of emotion was not significant, F (2, 106) = 0.43, p = .655; the interaction between emotion and loneliness was also not significant, F (2, 106) = 0.44, p = .645.

Fixed Effects (Coefficient Estimates): According to fixed effect estimates, the main effect of loneliness on approach velocity was not statistically significant, B = 0.00007, t (83.15) = 0.46, p = .644 (Table 26). In addition, no significant main effects were observed for depression, F (1, 51) = 0.43, p = .516, or social anxiety, F (1, 51) = 1.70, p = .198.

Table 26. Fixed Effects Estimates from the Linear Mixed Model Predicting Approach Velocity (RU Experiment)

Predictor	Estimate (B)	SE	df	t	95% CI (Lower, Upper)	*p*
Intercept: Neutral	0.00858	0.00120	92.59	7.13	[0.00619, 0.01097]	**<.001*****
Happy vs Neutral	0.00073	0.00111	106.00	0.65	[–0.00148, 0.00293]	.515
Angry vs Neutral	0.00099	0.00111	106.00	0.89	[-0.00122, 0.00320]	.375
Loneliness	0.00007	0.00015	83.15	0.46	[-0.0022, 0.00036]	.644
Depression	0.00016	0.00025	51.00	0.65	[-0.00034, 0.00067]	.516
Social Anxiety	–0.00021	0.00016	51.00	–1.31	[-0.00053, 0.00011]	.198
Happy ✻ Loneliness	0.00003	0.00012	106.00	0.24	[-0.00021, 0.00027]	.812
Angry ✻ Loneliness	0.00011	0.00012	106.00	0.91	[-0.00013, 0.00036]	.367

Note. Loneliness, depression, and social anxiety were mean centred prior to analysis.

Estimated Marginal Means: Estimated marginal means (EMMs) of approach velocity were highest in the angry condition (M = 0.00957, SE = 0.00120), followed by happy (M = 0.00931, SE = 0.00120), and the neutral condition (M = 0.00858, SE = 0.00120).

Loneliness Slope and Pairwise Comparisons: Simple slopes analyses indicated that the slope of loneliness was non-significant in the neutral condition (B = 0.00007, p = .644), the happy condition (B = 0.00010, p = .509), and the angry condition (B = 0.00018, p = .225). Pairwise comparisons of loneliness slopes between emotional conditions were also non-significant (all $ps \geq .64$; Table 27), indicating that the association between loneliness and approach velocity did not differ across facial emotions.

Table 27. Pairwise Comparisons of Loneliness Slopes by Emotion for Approach Velocity (RU Experiment)

Contrast	Estimate (B)	SE	df	t	95% CI (Lower, Upper)	*p*
Neutral vs Happy	–0.00073	0.00111	106	-0.65	[–0.00337, 0.00192]	0.791
Neutral vs Angry	–0.00099	0.00111	106	-0.89	[–0.00364, 0.00165]	0.647
Happy vs Angry	–0.00026	0.00111	106	-0.24	[–0.00291, 0.00238]	0.969

Note: No significant pairwise differences were observed between emotional conditions (all p > .64). Tukey adjustment applied for multiple comparisons (family of 3 emotions).

As illustrated in Figure 58, the lines are nearly parallel and overlap substantially across all levels of loneliness and emotion conditions (neutral, happy, angry). These findings suggest that the speed of approach-oriented responses did not vary according to emotional facial expression or the level of loneliness.

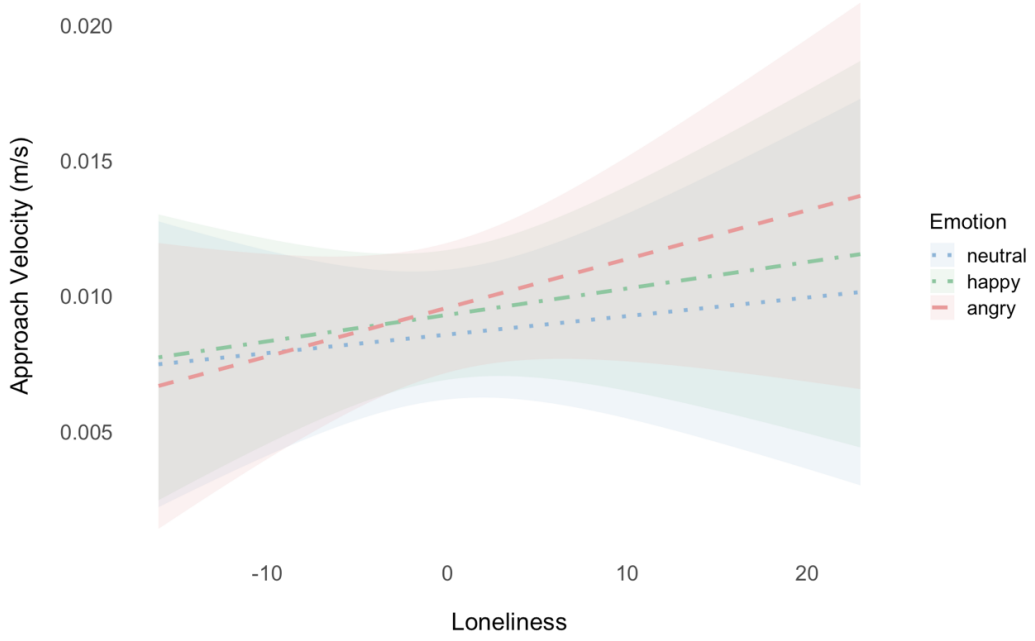


Figure 58. Interaction Between Loneliness and Emotion on Approach Velocity (RU Experiment)

Note: No significant effects or interactions emerged; approach velocity was similar across all emotions and levels of loneliness. Higher positive velocity indicates stronger approach, while more negative velocity indicates stronger avoidance.

4.2.2. Avoidance Velocity Response

Model Overview and Fit: LMM was conducted to examine whether avoidance-related velocity varied as a function of facial emotion, loneliness, depression, and social anxiety. The model explained 9.9% of the variance in avoidance velocity through fixed effects alone (*marginal* R^2 = .099), and 35.3% when accounting for both fixed and random effects (*conditional* R^2 = .353). The model's REML criterion at convergence was –1114.1. The random intercept variance for participants was estimated at 0.00001 (*SD* = 0.00324),

and the residual variance was 0.00003 (*SD* = 0.00517), indicating moderate between-participant variability in avoidance velocity.

Omnibus (Type III) ANOVA Results: A Type III analysis of variance using Satterthwaite's method indicated that the main effect of emotion was not significant, F (2, 106) = 1.06, p = .350. However, the interaction between emotion and loneliness was statistically significant, F (2, 106) = 3.48, p = .034.

Fixed Effects (Coefficient Estimates): According to the fixed effect estimates (Table 28), loneliness was significantly associated with avoidance velocity, B = 0.00034, t (119.64) = 3.43, p < .001, indicating that higher levels of loneliness were associated with faster avoidance-related responses. No significant main effects were observed for depression, F (1, 51) = 0.92, p = .343, or social anxiety, F (1, 51) = 0.24, p = .630.

Table 28. Fixed Effects Estimates from the Linear Mixed Model Predicting Avoidance Velocity (RU Experiment)

Predictor	Estimate (B)	SE	df	t	95% CI (Lower, Upper)	*p*
Intercept: Neutral	−0.00711	0.00082	133.5	−8.65	[−0.00874, −0.00548]	< .001
Happy vs Neutral	0.00085	0.00099	106	0.86	[−0.00110, 0.00280]	.391
Angry vs Neutral	−0.00058	0.00099	106	−0.59	[−0.00253, 0.00137]	.559
Loneliness	0.00034	0.00010	119.6	3.43	[0.00014, 0.00053]	< .001
Depression	−0.00014	0.00015	51.0	−0.96	[−0.00043, 0.00015]	.343
Social anxiety	0.00004	0.00009	51.0	0.49	[−0.00014, 0.00023]	.630
Happy ✻Loneliness	−0.00026	0.00011	106	−2.35	[−0.00047, −0.00005]	.021
Angry ✻Loneliness	−0.00024	0.00011	106	−2.21	[−0.00046, −0.00002]	.029

Estimated Marginal Means and Pairwise Comparisons: Estimated marginal means of avoidance velocity was highest for the happy condition, −0.0063 (*SE* = 0.0008), followed by the neutral condition, −0.0071 (*SE* = 0.0008), and lowest for the angry condition, −0.0077 (*SE* = 0.0008).

Loneliness Slope and Pairwise Comparisons: Simple slopes analyses revealed that loneliness was significantly associated with avoidance velocity in the neutral condition, $B = 0.00034$, $p < .001$, such that higher loneliness was associated with reduced avoidance speed. In contrast, the slopes of loneliness were not statistically significant in the happy ($B = 0.00008$, $p = .420$) or angry ($B = 0.00009$, $p = .337$) conditions. Pairwise comparisons of loneliness slopes between emotional conditions indicated trend-level differences between the neutral and happy conditions ($p = .053$) and between the neutral and angry conditions ($p = .074$), whereas the difference between happy and angry conditions was not significant ($p = .989$).

Table 29. Pairwise Comparisons of Loneliness Slopes by Emotion for Avoidance Velocity (RU Experiment)

Contrast	Estimate (B)	SE	df	t	95% CI (Lower, Upper)	*p*
Neutral vs Happy	0.00026	0.00011	106	2.35	[−0.000003, 0.000516]	.053†
Neutral vs Angry	0.00024	0.00011	106	2.21	[−0.000018, 0.000501]	.074†
Happy vs Angry	−0.00002	0.00011	106	−0.14	[−0.000275, 0.000244]	.989

Note. Tukey adjustment applied for multiple comparisons (family of 3 emotions). Kenward–Roger degrees of freedom.

As illustrated in Figure 59, loneliness appears to modulate avoidance velocity differently depending on the facial emotion. While avoidance velocity was reduced in neutral condition, the slopes in the happy and angry conditions were comparatively flat. The predicted lines diverged modestly across emotional conditions, visually reflecting the significant emotion × loneliness interaction observed in the model.

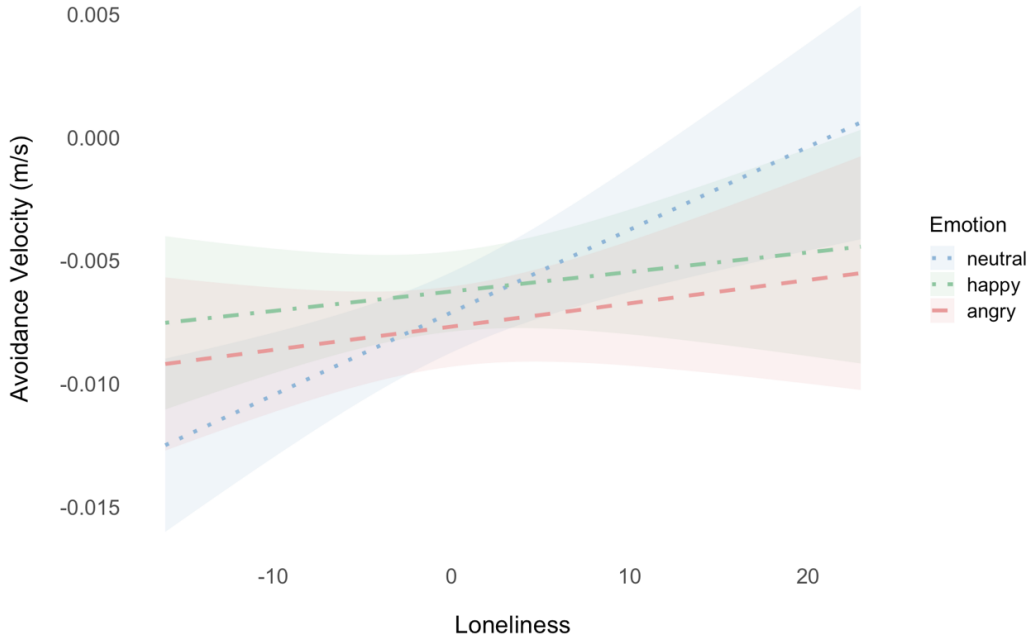


Figure 59. Interaction Between Loneliness and Emotion on Avoidance Velocity (RU Experiment)

Note. Higher positive velocity indicates stronger approach, while more negative velocity indicates stronger avoidance.

5. Discussion

This experiment aimed to investigate the interplay between facial emotional cues and individual differences in loneliness, depression, and social anxiety in modulating embodied postural and velocity of approach and avoidance responses during virtual social encounters. Based on the findings, a consistent pattern emerged: significant effects were primarily observed in avoidance amplitude and avoidance velocity, while approach-related responses remained relatively stable across emotions and loneliness level. This pattern underscores the differential sensitivity of approach and avoidance systems, with avoidance serving as a more dynamic marker of context-dependent social motivation in lonely individuals.

Firstly, avoidance amplitude and avoidance velocity revealed a clearer and more emotion-specific patterns in loneliness. Despite differences in data processing, both

measures converge to tell a coherent story, in which loneliness selectively modulated avoidance-related embodied responses, particularly towards ambiguous (neutral) or negative (angry) facial expressions. In terms of *avoidance amplitude* response, there was a significant trend in response to facial emotions depending on the loneliness level, and crucially, on the interaction between emotion and loneliness. Most notably, higher loneliness was significantly associated with *reduced* avoidance amplitude in response to *neutral* and *angry* faces, but not happy faces. This pattern might suggest that lonely individuals showed reduced withdrawal from ambiguous and negative cues, potentially reflecting disrupted the avoidance/repulsion system, as proposed by the Herding Model of Loneliness (Shamay-Tsoory & Kanterman, 2024). The amygdala's role in processing emotionally arousing stimuli (Adolphs et al., 2006) and its hyperactivity in chronic loneliness (Cacioppo et al., 2011) may explain why lonely individuals demonstrated reduced avoidance, their motivational system is dysregulated, impairing adaptive withdrawal. Meanwhile *avoidance velocity* was differentially modulated by loneliness. Here, loneliness was significantly associated with avoidance velocity in the neutral condition, such that higher loneliness was linked to slower avoidance velocity responses, whereas no such associations were observed for happy and angry expressions. Neutral faces lack clear emotional signals, which can increase uncertainty. In that regard, this finding contrasts with Automaticity Theory (Schneider & Chein, 2003), which posits that automatic processes, such as rapid withdrawal, are prioritised in uncertain or potentially threatening situations. Hence, the pattern found might mean that loneliness in ambiguous cues may be associated with reduced embodied reactivity rather than heightened automatic avoidance.

In terms of *approach amplitude and approach velocity*, neither emotional expression nor loneliness, nor their interaction, were significantly associated with approach responses. Although there were weak, non-significant findings suggesting slightly greater approach amplitude to angry and neutral faces at the higher levels of loneliness, and approach responses to happy faces remained relatively flat across loneliness levels, these effects did not reach conventional statistical significance. In summary, approach response appeared relatively stable across emotional cues and loneliness level, suggesting that approach behaviour may not be modulated by loneliness.

These findings support the conceptual distinction between approach and avoidance systems (Shamay-Tsoory & Kanterman, 2024; Carver, 1996) and suggest a differential sensitivity of behavioural systems: approach behaviour appears to be a relatively "default" or baseline mode, resistant to modulation by either social-emotional context or individual differences in loneliness and affect. Meanwhile, avoidance behaviours, by contrast, are more finely attuned to the intersection of social threat/reward cues and the internal state of lonely individuals.

6. Conclusion

This study highlights a clear dissociation between approach and avoidance behaviours in loneliness. While approach responses remained stable across emotions and loneliness levels, avoidance responses, particularly in amplitude and velocity, were strongly modulated by both emotional context and loneliness. These findings suggest that loneliness primarily alters withdrawal-related behaviour, especially in response to ambiguous or negative social cues, while engagement with positive cues remains blunted.

Validation Study

Validation and Selection of Virtual Emotional Face Stimuli

1. Introduction

Face datasets have been widely used in cognitive psychology (Ali et al., 2021; Tolba et al., 2006) and computational research (Tang et al., 2024) to investigate how people perceive and process different facial emotions. These datasets typically involved static images of human faces (Rinck et al., 2022; Cassidy et al., 2022). However, the use of virtual (i.e., computer-generated) faces is still relatively new in psychology research (Di Natale et al., 2024; Crookes et al., 2015), particularly in immersive VR environments. Hence, unlike real human face datasets, there is currently no adopted and validated dataset of virtual agent faces specifically designed for emotion recognition research.

Therefore, a set of custom-designed virtual agents displaying distinct emotional expressions was included in Experiment 1; these agents had been previously used in several studies conducted at Radboud University. Drawing on the insights from Experiment 1, the emotional range of virtual faces was expanded to fear and sad emotions to include in Experiment 2. Although these two emotions play crucial roles in social cognition and interpersonal communication; they are often underrepresented. Moreover, based on previous studies, fear and sad facial emotions are frequently misclassified or confused with neutral facial emotion (Chang et al., 2021). Therefore, including these facial emotions would provide an opportunity to assess whether virtual

agents could effectively convey more subtle or negatively valanced emotions in a VR context. Hence, this study was essential to validate the virtual faces to ensure each emotional expression was perceived by participants in line with its intended emotion.

Consequently, this validation study aimed to evaluate which virtual faces were accurately recognised and whether certain virtual faces were inherently more challenging to identify in each virtual face displayed by different actors.

2. Methods

Participants: Twenty participants (65% female; M_{age} = 33.3) were recruited for an online study designed on the Gorilla Experiment Builder (Anwyl-Irvine et al., 2020). All participants were informed about the purpose of the study and gave their consent. This study did not require ethical approval in accordance with institutional guidelines.

Materials: Sixty virtual faces (30 female and 30 male faces) were designed to depict five emotions (neutral, happy, sad, angry, fear; Figure 60) displayed by both female- and male-presenting virtual agents.

Procedure: Participants were presented with a virtual face displaying an emotion and instructed to select the emotion among six different responses. The *'surprised'* emotion was included in the response option to assess potential confusion between fear and surprise, as these two emotional expressions are often visually similar (Roy-Charland et al., 2014). There was no time limit to view the virtual faces, and they were presented with the responses on the same screen at the same time (Figure 61). Trials were randomised to reduce order effects.

Figure 60. Example of Virtual Avatars Displaying Five Emotional Expressions Across Genders

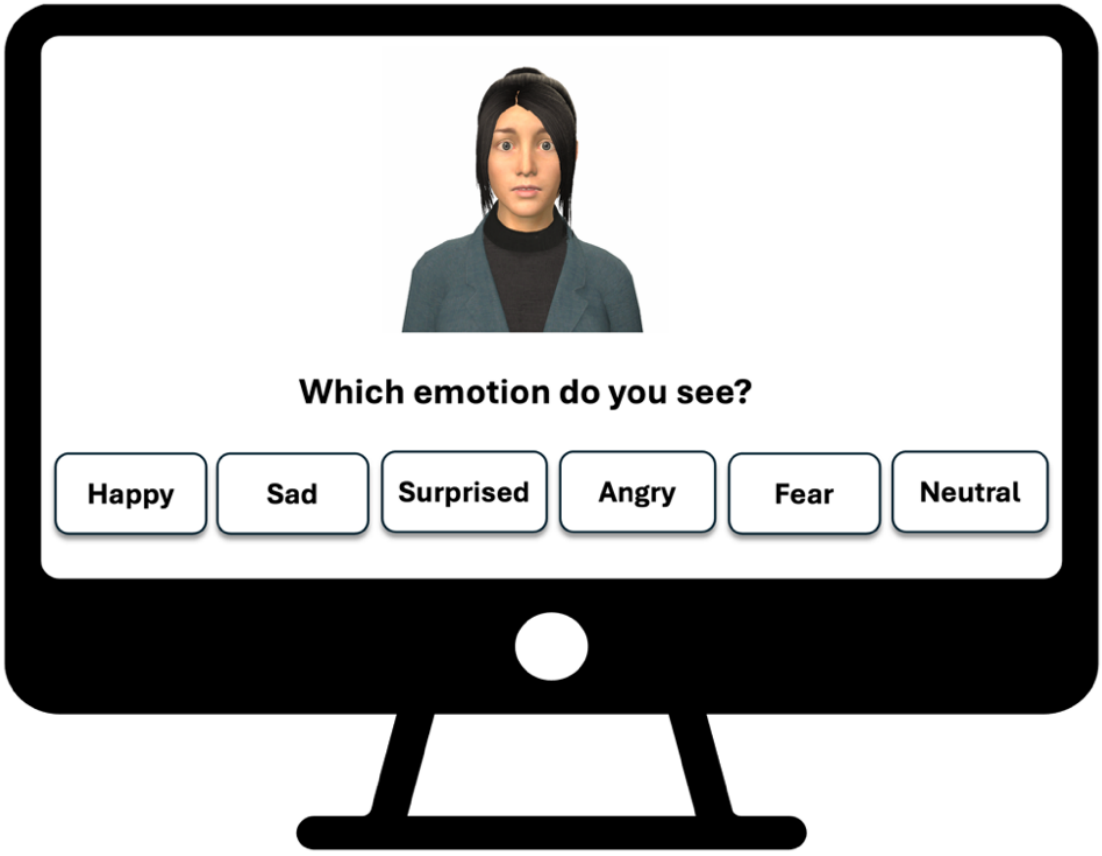


Figure 61. Example Trial from Virtual Facial Emotion Recognition Task

Design: Descriptive frequency analysis was conducted in Jamovi software to assess the emotion recognition accuracy of each virtual agent's facial expressions. The heatmap for the visualisation was generated in *R* Studio software. The independent variables were emotion expressed by the virtual face (neutral, happy, sad, angry, fear) and the identity of the virtual agent; and dependent variable was the emotion recognition accuracy. misclassification was noted to inform stimulus selection for Experiment 2. Accuracy was reported as the percentage of correct responses for each emotion–agent pair, and cross-tabulation of categorical variables (emotion × agent) was used to examine accuracy and misclassification patterns, which informed stimulus selection for Experiment 2.

3. Results

The average accuracy rates across five facial emotion categories (Neutral, Happy, Angry, Sad, Fear) were 72.5%, indicating good recognition of emotions of the virtual faces. In terms of emotion-level accuracy, happy was the most accurately recognised emotion with a 92.4% accuracy rate, and it was followed by angry emotion with 90% accuracy rate. Sad emotion was rated 88% correctly, and neutral emotion had 75% accuracy rete with minimal misclassification. Meanwhile, fear emotion consistently showed the lowest accuracy across agents with 45%, with frequent misclassification as surprised emotion.

In terms of face-level accuracy, fear emotion demonstrated significant variability. For instance, actor F1 was the least accurately recognised virtual face, averaging only 30%, with 65% misclassifying as surprised. M7 had the highest correct recognition with a 60% rate. On the other hand, happy faces consistently showed the highest recognition accuracy across different virtual faces (F1, F3, F8 and F8 with 95% accuracy; F2 and F5

with 85% accuracy). Sad, angry and neutral faces also demonstrated high recognisability, ranging from a minimum of 75% to a maximum of 100% recognition. Notably, male agents generally elicited higher recognition accuracy for "fear" compared to female virtual faces (Figure 62).

Overall, neutral faces were occasionally confused with happy, but the confusion rate remained low (5%). Happy, sad, and angry faces showed minimal misclassification, indicating strong recognizability. However, fear was the most misclassified emotion as surprise across virtual agents.

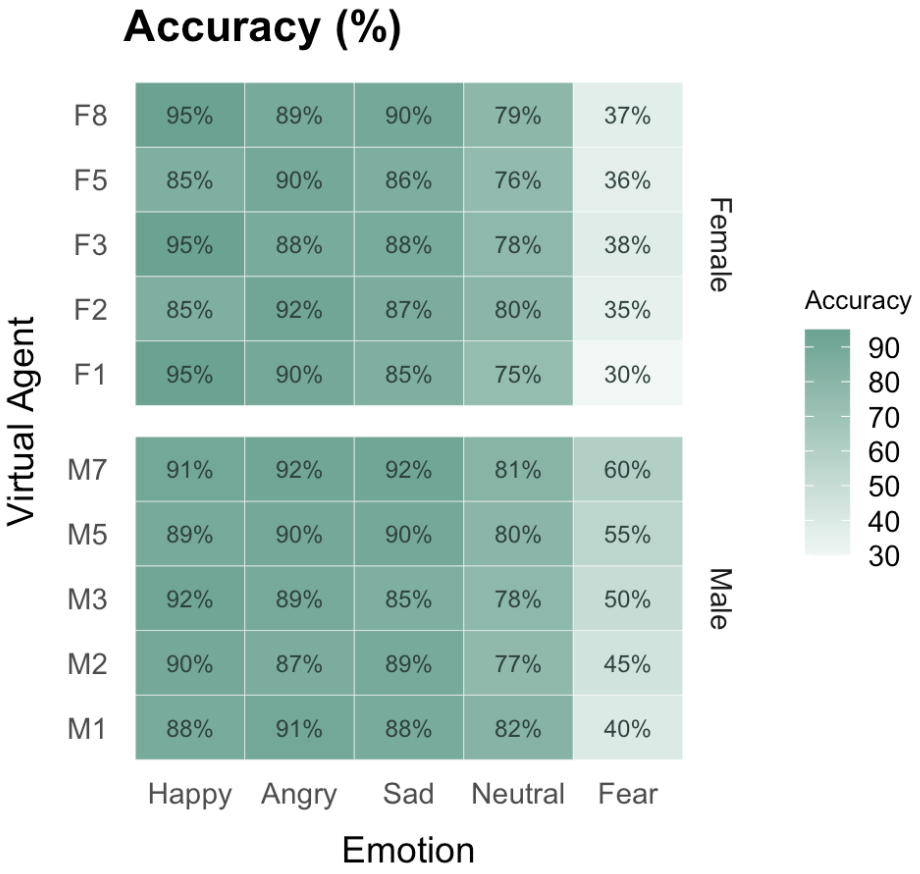


Figure 62. Emotion Recognition Accuracy (%) by Virtual Agent and Emotion

Note: Colour intensity corresponds to the level of accuracy, with darker shades indicating higher values.

4. Discussion

This validation study investigated variability in the recognition of emotions using virtual faces. The results indicated that happy and sad faces are the most accurately recognised, and fear is the least recognised facial emotion. Misclassification trends suggested that fear expressions were particularly misinterpreted as surprised expressions. Although the pilot study had a small sample size, it provided a foundation for understanding accuracy and misclassification patterns in virtual emotion recognition.

5. Conclusion

Findings suggest that while some emotions are consistently recognised (such as neutral, happy, sad, angry), others (such as fear) lead to misinterpretation, emphasising the importance of virtual stimuli design and response option selection in emotion research. Due to low recognition and high misclassification rates, fear faces were not included in the Experiment 2, despite of its relevance to loneliness research, to ensure that only the most recognisable stimuli are used to enhance the validity and reliability of future findings.

Experiment 2

1. Introduction

Experiment 2 was conducted at the Virtual Reality Lab at the University of East Anglia (UEA) in Norwich, United Kingdom, as part of a research collaboration. The VR environment used in this study was based on the platform developed at Radboud University and was adapted for use at UEA. Building on these technological foundations in the Experiment 1 and the insights from the Pilot Study, Experiment 2 was designed to address the following key research questions and to explore how loneliness modulates embodied approach-avoidance responses to emotional cues in a dynamic virtual environment:

RQ1. Does loneliness influence approach and avoidance responses (embodied postural responses in amplitude and velocity) towards facial emotions (neutral, happy, angry, sad) in a virtual space?

RQ2. How do individual differences in loneliness, depression, social anxiety, and alexithymia predict variations in embodied approach-avoidance towards emotional facial stimuli in a virtual space?

2. Methods

2.1. Participants

A priori power analysis was conducted using G*Power 3.1 to determine the required sample size for detecting a medium effect size ($f^2 = 0.15$) with $\alpha = .05$ and power $(1 - \beta) = .80$ in a multiple regression analysis with k predictors. The analysis indicated

that a minimum of N = 92 participants was required. Hence, a total of 94 participants (62 females, 66.0%) took part in the study. Participants ranged in age from 19 to 73 years (M = 25.93, SD = 9.04). Demographic characteristics of participants and scale scores across are presented in Table 30.

Table 30. Participant Demographics and Descriptive Statistics (N = 94)

Age Mean (+/- SD)	25.93 (9.04)	***Employment***	
Sex		*Student*	55 (58.5%)
Female	62 (66%)	*Full-time employed*	21 (22.3%)
Male	32 (34%)	*Part-time employed*	9 (9.6%)
Education level		*Homemaker*	2 (2.1%)
Highschool	60 (63.8%)	*Retired*	4 (4.3%)
Bachelor's degree	8 (8.5%)	*Unemployed*	3 (3.2%)
Master's degree	21 (22.3%)	***Ethnicity***	
PhD	5 (5.3%)	*White*	66 (70.2%)
Relationship status		*Black or Black British – African*	4 (4.3%)
Single	38 (40.4%)	*Asian or Asian British – Indian*	3 (3.2%)
In a relationship	44 (46.8%)	*Mixed – White and Black African*	4 (4.3%)
Married	11 (11.7%)	*Chinese*	6 (6.4%)
Separated	1 (1.1%)	*Arab*	6 (6.4%)
Living condition		*Asian*	5 (5.3%)
Alone	10 (10.6%)	***Scales***	
With parents	4 (4.3%)	*Loneliness Mean (+/- SD)*	42.30 (9.05)
With other family members	2 (2.1%)	*Depression Mean (+/- SD)*	10.33 (5.71)
With friends or shared house	56 (59.6%)	*Social Anxiety Mean (+/- SD)*	12.14 (4.49)
With partner/husband/wife	22 (23.4%)	*Alexithymia (+/- SD)*	27.9 (9.42)

2.2. Measures

Demographic variables: All participants completed a questionnaire to collect sociodemographic variables such as biological age, sex, education level, relationship status, living condition, employment and ethnicity.

Loneliness: The UCLA Loneliness Scale (Version 3; Russell, 1996) was used to measure participants' loneliness levels. The instrument consists of 20 items (e.g., *"How often do*

you feel left out?"). Responses vary on a scale from 1 (*never*) to 4 (*often*). Total scores range from 20 to 80. Internal consistency in this sample was excellent (α= .91).

Depression: The Center for Epidemiologic Studies Short Depression Scale (Ces-D-R-10; Radloff, 1977), a 10-item self-report scale designed to measure depressive symptomatology, was used. Items are rated on a four-point scale (from *0=rarely or none of the time* to *3=most or all the time*). Total scores range from 0 to 30, with higher scores representing a more depressed mood. Internal consistency in this sample was very good (α= .84).

Social anxiety: Social Interaction Anxiety-6 (SIAS-6; Peters et al., 2012) was used to measure participants' level of social anxiety regarding initiating and maintaining social connections. The items were measured on a 5-point Likert scale (*from 0=Not at all to 5=Extremely*). Total scores range from 0 to 24 with recommended cut-off score 7 or higher (Zsio et al., 2021). Internal consistency in this sample was very good (α= .84).

Alexithymia: The Toronto Alexithymia Scale (TAS; Bagby et al., 1994) was used to measure alexithymia, a 5-point Likert-type measure (from *1=strongly disagree to 5=strongly agree*) with scores of 52–60 indicating possible alexithymia, and scores above 60 indicating alexithymia. The full scale consists of three dimensions: difficulty identifying feelings (DIF; 7 items), difficulty describing feelings (DDF; 5 items), and external-oriented thinking (EOT; 8 items). In the current study only DIF and DDF dimensions were used, hence, producing a total score range of 12 to 36. Internal consistency in this sample was good (α= .82).

2.3. Materials

While most agents and stimuli were retained from Experiment 1 for consistency, the set was refined to include the clearest exemplars across all four emotional conditions: neutral, happy, angry, and sad revealed in the validation study (Figure 63).

Figure 63. Example Computer-Generated Virtual Facial Expressions of Neutral, Happy, Sad, and Anger across Genders used in the Affective Approach Avoidance VR Paradigm in UEA Experiment

The VR experiment was conducted using the Pico Neo 3 headset, and a wide 98° field of view for immersive, realistic visuals (Pico Interactive, 2024). The headset's Fresnel lenses allowed for adjustable interpupillary distance (54–73mm), ensuring comfortable fit and clear visuals for all participants.

2.4. Procedure, Data Processing, and Design

The procedure for Experiment 2 closely followed that of Experiment 1, originally conducted at Radboud University, with only a few key modifications (Figure 64). The

study was carried out in the VR lab at the University of East Anglia and involved an expanded sample of 94 participants and increased the number of trials to 16 to enhance statistical power and variability. While the VR task structure remained consistent, a fourth facial expression (sad emotion) was added to the existing set (neutral, happy, angry) to broaden emotional coverage. Additionally, participants completed a revised set of post-task self-report measures: different versions of the depression and social anxiety scales were used to improve measurement sensitivity, and an alexithymia measure was added as it is associated with both loneliness and difficulties in facial emotion processing. Compensation was provided via course credit through the SONA system or entry into a prize draw, with ten randomly selected participants receiving £10.

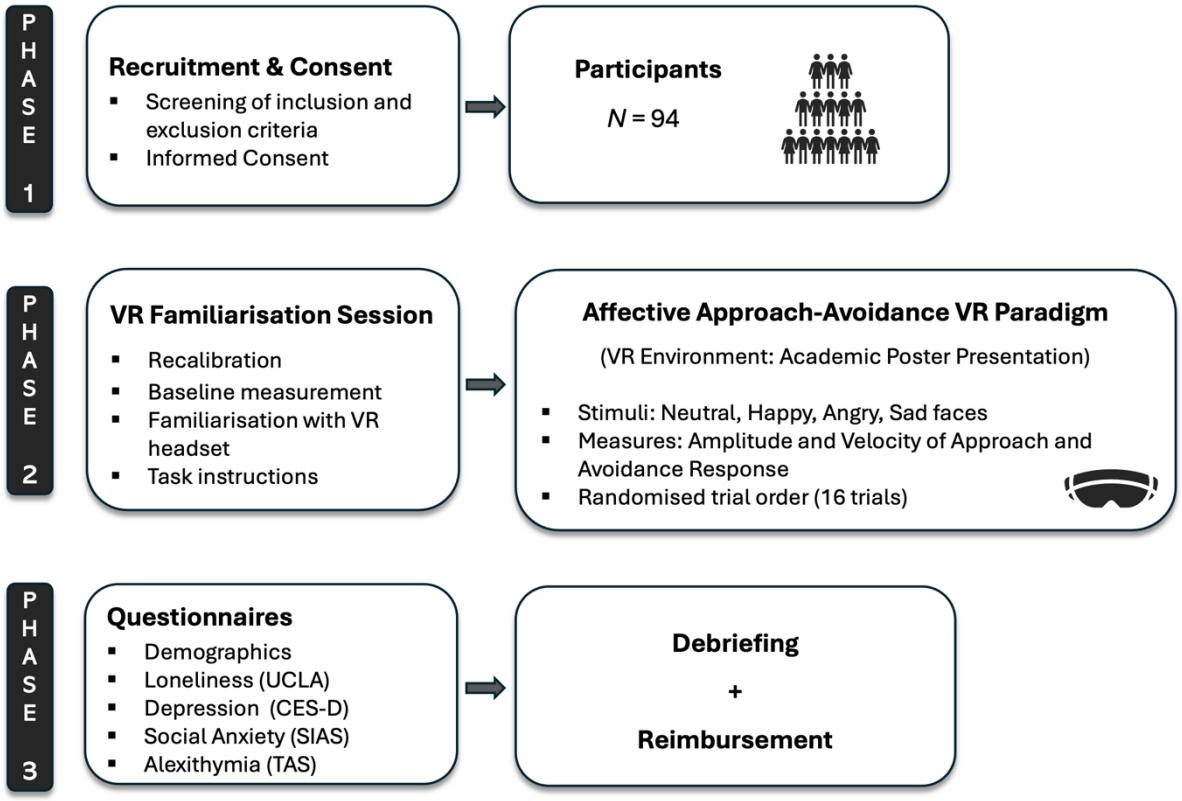


Figure 64. Experiment Flow of the Affective Approach-Avoidance VR Paradigm (UEA Experiment)

The Experiment 2 also followed the same data processing strategy and statistical design as the Experiment 1, including linear mixed-effects models (LMMs) with facial emotion as a within-subject factor and psychological traits (loneliness, depression, social anxiety, alexithymia) as continuous predictors. A Type III ANOVA was also used within the LMM framework to assess the overall significance of facial emotion, loneliness, and their interaction before interpreting specific effects.

We also applied the same temporal analysis of body sway to the UEA, visualising postural dynamics across all 16 trials (Figure 65). Outlier detection in Experiment 2 followed the same procedure as Experiment 1; emotion-specific extreme values were retained to avoid biasing the results or underestimating true emotional variability.

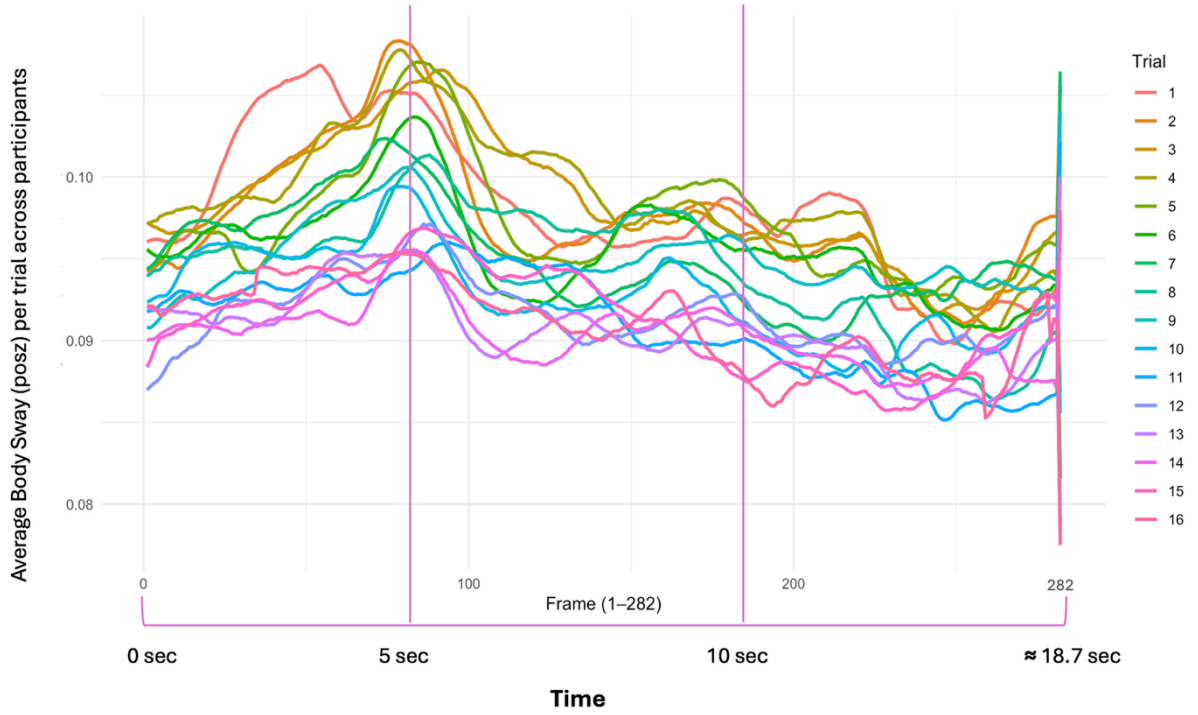


Figure 65. Temporal Dynamics of Body Sway in Response to Virtual Agent Proximity (Trials 1–16; UEA Experiment)

Note: Average body sway (posz) across 282 frames (~18.7 seconds) for each of 12 trials, aggregated across participants. Vertical blue lines denote timepoints at 0, 5, and 10 seconds. A consistent peak in sway is observed around 5 seconds, the point at which the virtual agent stops at ~1m distance from the participant. This moment appears to elicit a systematic embodied response across trials, suggesting increased postural adjustment. Post-approach, sway levels decrease, indicating possible postural stabilisation.

2.5. Ethics

The study was approved by the UEA PSY ethics committee (ETH2324-0804) and was registered on OSF (https://osf.io/pm7r2/resources). All participants were treated following APA ethical guidelines (American Psychological Association, 2017). Also, the study was conducted in accordance with the principles expressed in the Declaration of Helsinki (World Medical Association, 2013). Moreover, as the research involve human participation, the Research Ethics Code of Practice was followed.

3. Results

3.1. Amplitude of Embodied Postural Responses to Emotional Stimuli

3.1.1. Approach Amplitude Response

Model Overview and Fit: An LMM was conducted to investigate whether approach-related postural responses varied as a function of facial emotion, loneliness, depression, social anxiety, and alexithymia. The model explained 8% of the variance in approach amplitude through fixed effects alone (*marginal* R^2 = .080), and 19.9% when accounting for both fixed and random effects (*conditional* R^2 = .199). The model's REML criterion at convergence was –1721.6. The random intercept variance for participants was estimated at 0.00006 (*SD* = 0.00746), and the residual variance was 0.00037 (*SD* = 0.01935), indicating substantial between-participant variability in approach responses.

Omnibus (Type III) ANOVA: A Type III ANOVA with Satterthwaite's approximation indicated that the main effect of emotion on approach amplitude was statistically

significant, F (3, 276) = 8.21, p < .001. However, the interaction between emotion and loneliness was not significant, F (3, 276) = 0.71, p = .546.

Fixed Effects (Coefficient Estimates): The fixed effects estimates (Table 31) revealed that loneliness was not significantly associated with approach amplitude, β = 0.00051, SE = 0.00030, t (224.9) = 1.71, p = .088, depression and alexithymia were also not significantly associated with approach amplitude. However, higher social anxiety was significantly associated with reduced approach responses, β = –0.00079, SE = 0.00036, t (89) = –2.19, p = .031.

Table 31. Effect Estimates from the Linear Mixed Effects Model Predicting Approach Amplitude (UEA Experiment)

Predictor	Estimate (B)	SE	df	t	95% CI [Lower, Upper]	*p*
Intercept: Neutral	0.01405	0.00214	345.1	6.57	[0.00984, 0.01830]	**< .001*****
Angry vs Neutral	0.00548	0.00282	276.0	1.94	[–0.00008, 0.01103]	.053†
Happy vs Neutral	–0.00703	0.00282	276.0	–2.49	[–0.01260, –0.00146]	**.013***
Sad vs Neutral	–0.00560	0.00282	276.0	–1.98	[–0.01120, –0.00001]	**.048***
Loneliness	0.00051	0.00030	224.9	1.71	[–0.00008, 0.00109]	.088†
Depression	0.00025	0.00034	89.0	0.73	[–0.00043, 0.00092]	.470
Social Anxiety	–0.00079	0.00036	89.0	–2.19	[–0.00151, –0.00007]	**.031***
Alexithymia	–0.00023	0.00018	89.0	–1.25	[–0.00060, 0.00013]	.213
Angry ✻ Loneliness	0.00010	0.00031	276.0	0.32	[–0.00052, 0.00072]	.749
Happy ✻ Loneliness	–0.00030	0.00031	276.0	–0.96	[–0.00092, 0.00032]	.338
Sad ✻ Loneliness	–0.00022	0.00031	276.0	–0.70	[–0.00084, 0.00040]	.483

Note. The reference level for emotion is neutral. A random intercept for participant ID was included. Bolded p-values are significant at p < .05. CI = confidence interval. All continuous predictors were mean centred prior to analysis. Estimate (B) is an unstandardized regression coefficient.

Estimated Marginal Means: Estimated marginal means indicated that approach amplitude was highest for angry expressions (M = 0.01953, SE = 0.00214), followed by neutral (M = 0.01405, SE = 0.00214), sad (M = 0.00845, SE = 0.00214), and happy expressions (M = 0.00701, SE = 0.00214).

Loneliness Slopes and Pairwise Comparisons: Simple slope analyses indicated positive associations between loneliness and approach amplitude across all emotional conditions, with the largest slope observed for angry expressions (β = 0.00061, *SE* = 0.00030), followed by neutral (β = 0.00051, *SE* = 0.00030), sad (β = 0.00029, *SE* = 0.00030), and happy expressions (β = 0.00021, *SE* = 0.00030). Among these, the association between loneliness and approach amplitude reached statistical significance only for angry faces, t (225) = 2.05, p = .041 (Figure 66), whereas slopes for neutral, sad, and happy expressions were not significant (*ps* ≥ .088). Exploratory Tukey-adjusted pairwise comparisons of loneliness slopes between emotional conditions (Table 32) revealed no significant differences between any emotion pairs (all *ps* ≥ .576). Consistent with the non-significant omnibus interaction, these findings indicate that although loneliness showed a numerically stronger association with approach responses to angry faces, there was no robust evidence that the loneliness–approach relationship differed across emotional expressions.

Table 32. Pairwise Comparisons of Loneliness Slopes by Emotion for Approach Amplitude (UEA Experiment)

Contrast	Estimate (β)	SE	df	t	95% CI [Lower, Upper]	*p*
Neutral vs Happy	0.00030	0.00031	276	0.96	[−0.00017, 0.00077]	.772
Neutral vs Angry	−0.00010	0.00031	276	−0.32	[−0.00057, 0.00037]	.989
Neutral vs Sad	0.00022	0.00031	276	0.70	[−0.00025, 0.00069]	.896
Happy vs Angry	−0.00040	0.00031	276	−1.28	[−0.00087, 0.00007]	.576
Happy vs Sad	−0.00008	0.00031	276	−0.26	[−0.00056, 0.00038]	.994
Angry vs Sad	0.00032	0.00031	276	1.02	[−0.00016, 0.00078]	.736

Note. Pairwise comparisons assess whether the predictive slopes of loneliness on approach amplitude differ between emotional conditions. p*-values were adjusted using Tukey's method to control for multiple comparisons. β = Standardized coefficient.*

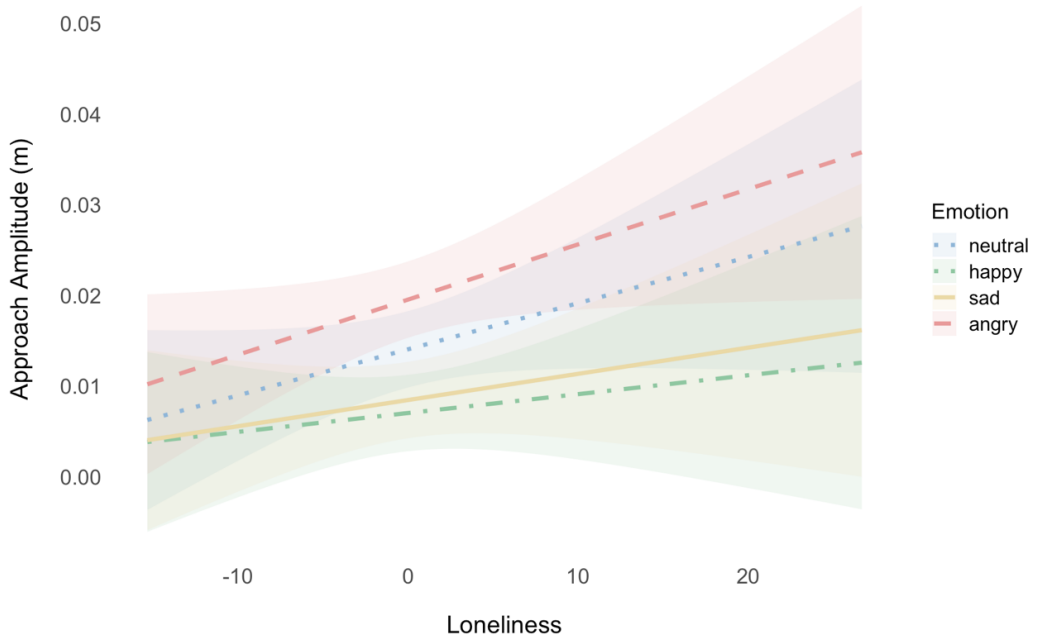


Figure 66. Interaction Between Loneliness and Emotion on Approach Amplitude Responses (UEA Experiment)

Note. Loneliness was mean-centred. Approach amplitude is reported in meters (m), with higher values indicating greater forward approach movement.

3.1.2. Avoidance Amplitude Response

Model Overview and Fit: An LMM was conducted to investigate whether avoidance-related postural responses varied as a function of facial emotion, loneliness, depression, social anxiety, and alexithymia. The model explained 9.5% of the variance in avoidance amplitude via fixed effects alone (*marginal* R^2 = .095) and 15.1% of the variance when including both fixed and random effects (*conditional* R^2 = .151). The REML criterion at convergence was –1820.1. The random intercept variance for participants was estimated at 0.00002 (*SD* = 0.00444), and the residual variance was 0.00030 (*SD* = 0.01740).

Omnibus (Type III) ANOVA: A Type III ANOVA with Satterthwaite's approximation a revealed a significant main effect of emotion on avoidance amplitude, F (3, 276) = 10.14, p < .001. The interaction between emotion and loneliness was not significant F (3, 276)

= 0.87, p = .458, suggesting that the relationship between loneliness and avoidance amplitude did not differ across emotional expressions.

Fixed Effects (Coefficient Estimates): According to the fixed effect estimates (Table 33), the main effect of loneliness on avoidance amplitude was statistically significant, β = 0.00053, SE = 0.00025, t (255.5) = 2.12, p = .035, indicating that higher loneliness was associated with stronger avoidance. Social anxiety was also significantly associated with avoidance amplitude, β = –0.00064, SE = 0.00029, t (89) = –2.21, p = .030. Depression and alexithymia were not significantly associated with avoidance amplitude.

Table 33. Fixed Effect Estimates from the Linear Mixed Effects Model Predicting Approach Amplitude (UEA Experiment)

Predictor	Estimate (B)	SE	df	t	95% CI [Lower, Upper]	*p*
Intercept: Neutral	0.01689	0.00185	360	9.12	[0.01325, 0.02050]	< **.001*****
Happy vs Neutral	–0.01022	0.00254	276	–4.03	[–0.01522, –0.00522]	< **.001*****
Sad vs Neutral	–0.01063	0.00254	276	–4.19	[–0.01563, –0.00563]	< **.001*****
Angry vs Neutral	–0.00113	0.00254	276	–0.44	[–0.00613, 0.00387]	.657
Loneliness	0.00053	0.00025	255	2.12	[0.00004, 0.00102]	**.035***
Depression	0.00008	0.00027	89	0.29	[–0.00045, 0.00061]	.772
Social Anxiety	–0.00064	0.00029	89	–2.21	[–0.00121, –0.00007]	**.030***
Alexithymia	–0.00019	0.00015	89	–1.29	[–0.00048, 0.00010]	.199
Happy ✻ Loneliness	–0.00024	0.00028	276	–0.86	[–0.00080, 0.00032]	.392
Sad ✻ Loneliness	–0.00038	0.00028	276	–1.34	[–0.00094, 0.00018]	.182
Angry ✻ Loneliness	–0.00001	0.00028	276	–0.02	[–0.00056, 0.00055]	.986

Note. The reference level for emotion is neutral. A random intercept for participant ID was included.

Estimated Marginal Means: Estimated marginal means indicated that avoidance amplitude was highest for neutral expressions (M = 0.01689, SE = 0.00185), followed by angry expressions (M = 0.01576, SE = 0.00185), and was substantially lower for sad (M = 0.00625, SE = 0.00185) and happy expressions (M = 0.00667, SE = 0.00185).

Loneliness Slopes and Pairwise Comparisons: Simple slope analyses indicated positive associations between loneliness and avoidance amplitude across all emotional conditions. The largest slopes were observed for neutral (β = 0.00053, *SE* = 0.00025) and angry expressions (β = 0.00053, *SE* = 0.00025), both of which reached statistical significance, *ts* (255) ≥ 2.10, *ps* ≤ .038. In contrast, the slopes for happy (β = 0.00029, *SE* = 0.00025) and sad expressions (β = 0.00015, *SE* = 0.00025) were not statistically significant (*ps* ≥ .181). Exploratory Tukey-adjusted pairwise comparisons of loneliness slopes between emotional conditions (Table 34) revealed no significant differences between any emotion pairs (all *ps* ≥ .539).

Table 34. Pairwise Comparisons of Loneliness Slopes by Emotion for Approach Amplitude (UEA Experiment)

Contrast	Estimate	SE	df	*t*	95% CI [Lower, Upper]	*p*
Neutral vs Happy	0.00024	0.00028	276	0.86	[–0.00032, 0.00080]	.827
Neutral vs Sad	0.00038	0.00028	276	1.34	[–0.00018, 0.00094]	.539
Neutral vs Angry	0.00001	0.00028	276	0.02	[–0.00055, 0.00056]	1.000
Happy vs Sad	0.00014	0.00028	276	0.48	[–0.00042, 0.00070]	.963
Happy vs Angry	–0.00024	0.00028	276	–0.84	[–0.00080, 0.00032]	.835
Sad vs Angry	–0.00037	0.00028	276	–1.32	[–0.00093, 0.00019]	.551

Note. Pairwise comparisons assess whether the predictive slopes of loneliness on approach amplitude differ between emotional conditions. p*-values were adjusted using Tukey's method to control for multiple comparisons*

Taken together, avoidance amplitude showed a clearer and more robust association with loneliness than approach amplitude. Higher loneliness was associated with increased leaning backward across emotional conditions, particularly for neutral and angry faces.

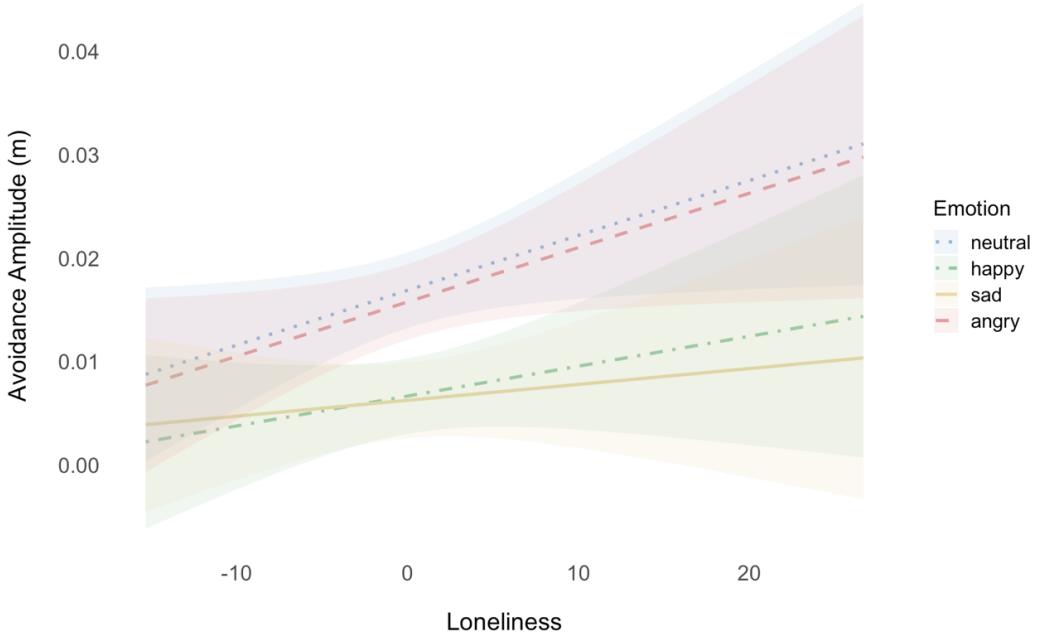


Figure 67. Interaction Between Loneliness and Emotion on Avoidance Amplitude Responses (UEA Experiment)

Note. Loneliness was mean-centred. Avoidance amplitude is reported in meters (m), with higher values indicating greater backward avoidance movement.

3.2. Velocity of Embodied Postural Responses to Emotional Stimuli

3.2.1. Approach Velocity Response

Model Overview and Fit: An LMM was conducted to investigate whether approach-related postural velocity varied as a function of facial emotion, loneliness, depression, social anxiety, and alexithymia. The model explained a very small proportion of the variance (0.6%) in approach velocity through fixed effects alone (*marginal* R^2 = .006) and a substantially larger proportion when accounting for both fixed and random effects (conditional R^2 = .659). The random intercept variance for participants was estimated at 0.00017 (*SD* = 0.01302), and the residual variance was 0.00010 (*SD* = 0.00982). The model's REML criterion at convergence was –2073.2.

Omnibus (Type III) ANOVA: The Type III ANOVA with Satterthwaite's approximation revealed no significant main effect of emotion, F (3, 276) = 1.35, p = .259, and no significant interaction between emotion and loneliness, F (3, 276) = 0.58, p = .627.

Fixed Effects (Coefficient Estimates): According to fixed effect estimates (Table 35), loneliness was not significantly associated with approach velocity, β = 0.00032, *SE* = 0.000191, t (89) = 1.65, p = .101 Depression, social anxiety, and alexithymia were also not significantly associated with approach velocity.

Table 35. Fixed Effects Estimates from the Linear Mixed-Effects Model Predicting Approach Velocity (UEA Experiment)

Predictor	Estimate (B)	SE	df	t	95% CI [Lower, Upper]	*p*
Intercept: Neutral	0.00548	0.00119	182	4.61	[0.00313, 0.00783]	< .001
Angry vs Neutral	0.00186	0.00111	276	1.68	[-0.00032, 0.00399]	.094
Happy vs Neutral	-0.00012	0.00111	276	-0.11	[-0.00230, 0.00207]	.914
Sad vs Neutral	0.00072	0.00111	276	0.65	[-0.00146, 0.00290]	.516
Loneliness	0.00032	0.000191	123	1.65	[-0.000063, 0.000695]	.101
Depression	0.000179	0.000263	89	0.68	[-0.000343, 0.000701]	.497
Social Anxiety	-0.000443	0.000281	89	-1.58	[-0.00100, 0.000117]	.118
Alexithymia	-0.000206	0.000143	89	-1.44	[-0.000490, 0.000078]	.155
Angry ✻ Loneliness	-0.000123	0.000123	276	-1.00	[-0.000365, 0.000123]	.317
Happy ✻ Loneliness	0.000009	0.000123	276	0.07	[-0.000233, 0.000252]	.940
Sad ✻ Loneliness	0.000018	0.000123	276	0.15	[-0.000224, 0.000260]	.882

*Note. All continuous predictors were mean centred prior to analysis. CI = confidence interval. † indicates effects approaching statistical significance (*p > .05*).*

Estimated Marginal Means: EMMs of approach velocity were highest for angry (*M* = 0.00735, *SE* = 0.00119), followed by sad (*M* = 0.00620, *SE* = 0.00119), neutral (*M* = 0.00548, *SE* = 0.00119), and happy faces (*M* = 0.00536, *SE* = 0.00119). Differences across emotions were modest and did not reach statistical significance.

Loneliness Slopes and Pairwise Comparisons: Simple slope analyses indicated that loneliness was not significantly associated with approach velocity for any emotional

condition (all *ps* ≥ .082), with confidence intervals consistently including zero. Tukey-adjusted pairwise comparisons of loneliness slopes across emotions (Table 36) revealed no significant differences between any emotion pairs (all *ps* ≥ .662).

Table 36. Pairwise Comparisons of Loneliness Slopes Across Emotions for Approach Velocity (UEA Experiment)

Contrast	Estimate (β)	SE	df	t	95% CI [Lower, Upper]	*p*
Neutral vs Happy	-0.000009	0.000123	276	-0.075	[-0.000327, 0.000309]	.999
Neutral vs Angry	0.000123	0.000123	276	1.00	[-0.000195, 0.000441]	.749
Neutral vs Sad	-0.000018	0.000123	276	-0.145	[-0.000336, 0.000300]	.999
Angry vs Happy	0.000132	0.000123	276	1.075	[-0.000186, 0.000450]	.705
Angry vs Sad	-0.000141	0.000123	276	-1.145	[-0.000459, 0.000177]	.662
Happy vs Sad	-0.000009	0.000123	276	-0.070	[-0.000327, 0.000309]	.999

Note. Pairwise comparisons assess whether the predictive slopes of loneliness on approach amplitude differ between emotional conditions. p*-values were adjusted using Tukey's method to control for multiple comparisons*

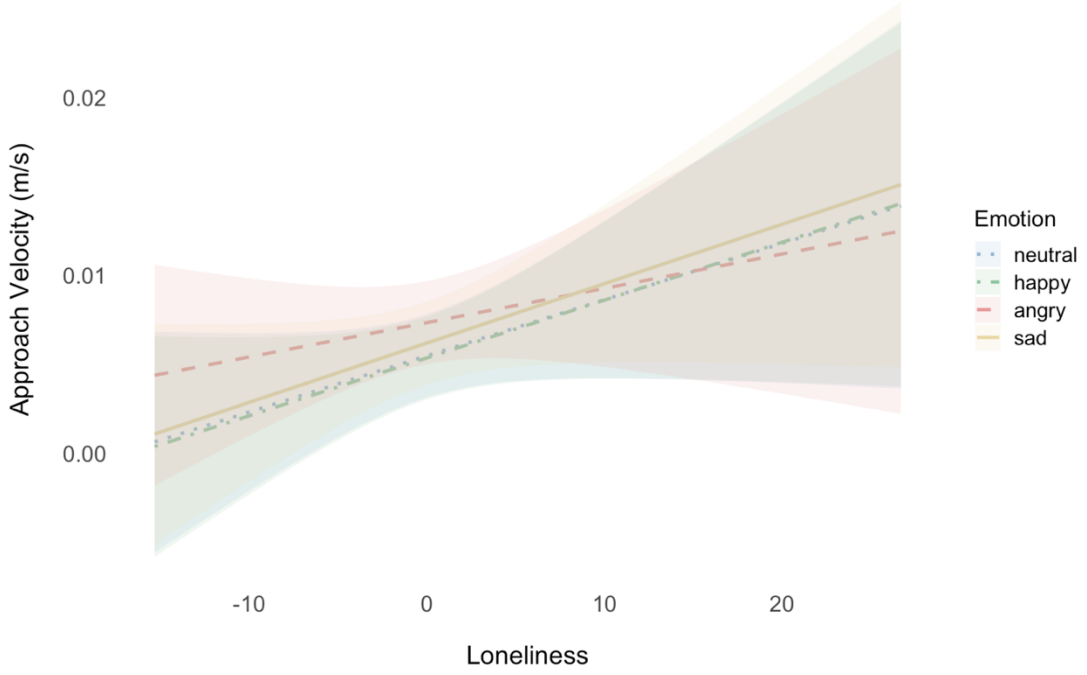


Figure 68. Interaction Between Loneliness and Emotion on Approach Velocity (UEA Experiment)

Note. Loneliness scores were mean-centred. Lines represent model-based estimated marginal means derived from the linear mixed-effects model, with shaded bands indicating 95% confidence intervals. Approach velocity is reported in metres per second (m/s), with higher values indicating faster forward approach movement. Predictions reflect fixed effects only. Approach velocity increased slightly with loneliness across emotions, with largely parallel slopes and overlapping confidence intervals, indicating no strong emotion-specific modulation.

3.2.2. Avoidance Velocity Response

Model Overview and Fit: An LMM was conducted to investigate whether avoidance-related velocity varied as a function of facial emotion, loneliness, depression, social anxiety, and alexithymia. The model explained 1.4% of the variance in avoidance velocity through fixed effects alone (*marginal* R^2 = .014), and 37.1% when accounting for both fixed and random effects (*conditional* R^2 = .371). The model's REML criterion at convergence was –2512.9. The random intercept variance for participants was estimated at 0.00002 (*SD* = 0.00446), and the residual variance was 0.00004 (*SD* = 0.00601), indicating modest between-participant variability in baseline avoidance velocity.

Omnibus (Type III) ANOVA: A Type III ANOVA with Satterthwaite's approximation revealed no significant main effect of emotion on avoidance velocity, F (3, 276) = 0.73, p = .534, and no significant interaction between emotion and loneliness, F (3, 276) = 1.53, p = .208, indicating that the relationship between loneliness and avoidance velocity did not differ across emotional expressions.

Fixed Effects (Coefficient Estimates): According to the fixed effects model (Table 37), loneliness was not significantly associated with avoidance velocity, β = -0.000104, *SE* = 0.0000567, t (142) = -1.83, p = .070. Depression, social anxiety, and alexithymia were likewise not significantly associated with avoidance velocity (all *ps* ≥ .222).

Estimated Marginal Means: Estimated marginal means indicated that avoidance velocity was highest for sad faces (*M* = –0.00429, *SE* = 0.000367), followed by angry (*M* = –0.00404, *SE* = 0.000367), neutral (*M* = –0.00409, *SE* = 0.000367), and happy faces (*M* = –0.00372, *SE* = 0.000367).

Table 37. Fixed Effects Estimates from the Linear Mixed-Effects Model Predicting Avoidance Velocity (UEA Experiment)

Predictor	Estimate (B)	SE	df	t	95% CI [Lower, Upper]	*p*
Intercept: Neutral	-0.00409	0.000367	229	-11.2	[-0.00482, -0.00337]	**< .001*****
Happy vs Neutral	0.000372	0.000391	276	0.95	[-0.000397, 0.00114]	.342
Sad vs Neutral	-0.000198	0.000391	276	-0.51	[-0.000967, 0.000571]	.612
Angry vs Neutral	0.000051	0.000391	276	0.13	[-0.000718, 0.000820]	.897
Loneliness	-0.000104	0.0000567	142	-1.83	[-0.000216, 0.0000084]	.070†
Depression	-0.0000203	0.0000749	89	-0.27	[-0.000169, 0.000128]	.787
Social Anxiety	0.0000776	0.0000799	89	0.97	[-0.0000810, 0.000236]	.334
Alexithymia	0.0000501	0.0000408	89	1.23	[-0.0000308, 0.000131]	.222
Happy × Loneliness	0.0000294	0.0000433	276	0.68	[-0.0000559, 0.000115]	.498
Sad × Loneliness	0.0000633	0.0000433	276	1.46	[-0.0000220, 0.000149]	.145
Angry × Loneliness	0.0000862	0.0000433	276	1.99	[0.0000009, 0.000172]	.048

Loneliness Slopes and Pairwise Comparisons: Simple slope analyses indicated that loneliness was not significantly associated with avoidance velocity for any emotional condition (all *ps* ≥ .070), with confidence intervals consistently including zero. Although sad and angry faces elicited numerically higher avoidance velocities than happy or neutral faces, these differences were modest and did not reach statistical significance (Figure 69). Tukey-adjusted pairwise comparisons of loneliness slopes across emotions (Table 38) revealed no significant differences between any emotion pairs (all *ps* ≥ .194), consistent with the non-significant omnibus interaction.

Table 38. Pairwise Comparisons of Loneliness Slopes Across Emotions for Avoidance Velocity (UEA Experiment)

Contrast	Estimate (β)	SE	df	t	95% CI [Lower, Upper]	*p*
Neutral vs Happy	-0.0000294	0.0000433	276	-0.679	[-0.000141, 0.000083]	.905
Neutral vs Sad	-0.0000633	0.0000433	276	-1.461	[-0.000175, 0.000049]	.462
Neutral vs Angry	-0.0000862	0.0000433	276	-1.989	[-0.000198, 0.000026]	.194
Happy vs Sad	-0.0000339	0.0000433	276	-0.782	[-0.000146, 0.000078]	.863
Happy vs Angry	-0.0000568	0.0000433	276	-1.311	[-0.000169, 0.000055]	.557
Sad vs Angry	-0.0000229	0.0000433	276	-0.528	[-0.000135, 0.000089]	.952

Note. Pairwise comparisons assess whether the predictive slopes of loneliness on approach amplitude differ between emotional conditions. p*-values were adjusted using Tukey's method to control for multiple comparisons.*

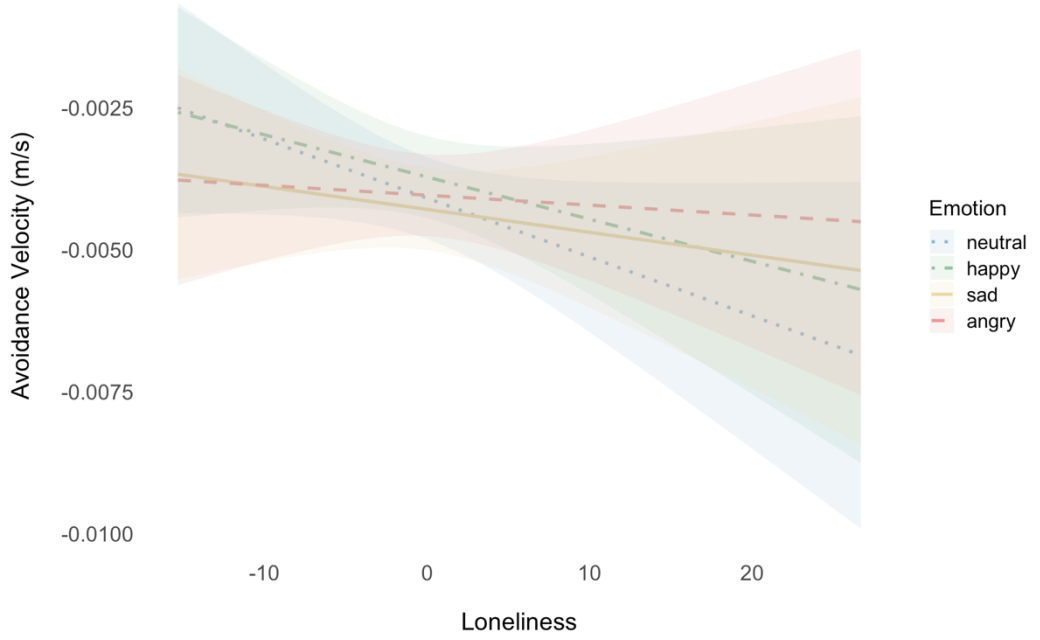


Figure 69. Interaction Between Loneliness and Emotion on Avoidance Velocity (UEA Experiment)

Note. Avoidance velocity is expressed in metres per second (m/s), with more negative values indicating faster backward (avoidance) response.

4. Discussion

The present experiment leveraged immersive VR to investigate the approach–avoidance behaviours by measuring the amplitude and velocity of embodied responses to emotional stimuli in virtual space, controlling for depression, social anxiety, and alexithymia, with a larger and more diverse sample than in Experiment 1 conducted at Radboud University. In contrast to the Experiment 1, the findings form the Experiment 2 at University of East Anglia revealed a more nuanced and partially disassociated pattern. The findings suggested that emotional expressions exerted robust main effects on amplitude responses, while loneliness demonstrated selective and modes associations, primarily with avoidance related responses rather than approach tendencies.

In terms of *avoidance amplitude*, the results showed clear and more consistent associations with loneliness. Higher loneliness was associated with greater avoidance across emotional conditions, with the strongest effects observed particularly for neutral and angry faces. Meanwhile, avoidance amplitude responses to happy and sad faces remained low and non-significant regardless of loneliness level. This pattern might indicate that loneliness is linked to increased avoidance, particularly in response to emotionally ambiguous or potentially threatening emotional cues. This finding aligns with the Evolutionary Theory of Loneliness (Cacioppo & Hawkley, 2009) which suggests that lonely individuals demonstrate hypervigilance to social threats and ambiguous cues, (such as angry and neutral faces). Additionally, it is consistent with the social monitoring hypothesis (Gardner et al., 2005), reflecting pre-attempted social withdrawal strategy for self-preservation. Neutral expressions, lacking clear emotional valence, may be interpreted through a negative cognitive bias lens of lonely individuals due to their heightened sensitivity to social threat. In fact, previous research reported that lonely individuals misinterpret neutral faces as negative emotions (Cheeta et al., 2021; Smith et al., 2021). From a neurobiological perspective, this pattern aligns with the Herding Model indicating hyperactivation of the amygdala-based avoidance or repulsion system in chronic loneliness (Shamay-Tsoory & Kanterman, 2024). The amygdala's role in integrating emotional salience with motor preparation might provide an explanation in which perceived social threat may be translated into avoidance through interpersonal distance.

By contrast, *avoidance velocity* was not robustly modulated by loneliness or emotion. However, a marginal negative association between loneliness and avoidance suggested a tendency towards faster avoidance at higher levels of loneliness. This aligns with prior

research showing that approach-avoidance biases are often graded rather than reflexive (Elliot, 2006). This disassociation between amplitude and velocity implies that loneliness may primarily influence the extent of withdrawal rather than the speed. Nevertheless, it is important to note that data processing methodologies (e.g., baseline definitions, time frame selection) between amplitude and velocity measures may have contributed this divergence.

In contrast to avoidance, *approach* related embodied responses demonstrated limited associations with loneliness. Neither approach amplitude nor approach velocity was significantly linked to loneliness across emotional conditions. Although, there was a marginal positive association between loneliness and approach amplitude to angry faces. The simultaneous approach and avoidance responses to angry faces might reflect the loneliness paradox. However, this finding should be interpreted given the absence of a significant interaction effect.

Moreover, it is equally important to note that loneliness was not associated with greater approach or avoidance towards happy facial expressions. This finding might suggest that lonely individuals may not necessarily avoid positive social cues. This pattern aligns with the reward circuitry dysfunction proposed by Shamay-Tsoory and Kanterman (2024), where chronic loneliness is associated with diminished activity in the ventral striatum and orbitofrontal cortex. The lack of embodied response to happy faces may reflect this underlying neurobiological change, where positive social stimuli fail to activate approach motivation systems effectively.

5. Conclusion

This study demonstrates that loneliness is linked to nuanced and sometimes conflicting embodied responses to social cues, marked by heightened avoidance of ambiguous threats and reduced engagement with positive stimuli. These patterns point to disrupted social motivational systems and highlight the complexity of loneliness beyond simple withdrawal.

Taken together, the findings suggest that embodied responses are primarily expressed through increased avoidance rather than approach, reinforcing the asymmetry between these motivational systems.

Chapter Conclusion

The two experiments in this chapter investigated embodied approach-avoidance biases (measured in amplitude and velocity) towards emotional stimuli in loneliness using immersive VR technology. Moreover, the current experiments move beyond attention and interpretation of facial emotion processing to reveal how these biases manifest in embodied behaviour, that is, how lonely individuals physically approach or avoid emotional cues in real time. By comparing these two experiments, key patterns emerged that enhance our understanding of AAB in loneliness, while also raising crucial theoretical and methodological considerations.

Across both experiments, a consistent and theoretically meaningful dissociation emerged between approach and avoidance biases. Approahc-related embodied responses, both amplitude and velocity, were mainly stable across emotional expressions and the level of loneliness. This might suggest that loneliness does not primarily influence approach motivation, and that approach motivation may be more stable and/or default response in social interactions. In contrast, avoidance-related responses were selectively modulated by loneliness, particularly to ambiguous (neutral) and negative (angry) facial emotional expressions. Particularly, avoidance amplitude (but not velocity), was significantly associated with loneliness, indicating that the extent of withdrawal, rather than its speed, is the key behavioural signature.

Moreover, consistently across both experiments, lonely individuals did not show increased avoidance or approach to happy faces. This is theoretically important. It might suggest that positive social cues may either buffer against withdrawal or simply fail to motivate lonely individuals, consistent with proposed dysfunction in the reward system

(ventral striatum, OFC) seen in chronic loneliness (Shamay-Tsoory & Kanterman, 2024). This assumption is further supported by the interpretation bias findings from the Scoping Review on Chapter 2. The findings showed that situational loneliness increased approach motivation, while chronic loneliness reinforced avoidance behaviour, reflecting the loneliness paradox between motivation to reconnect and fear of rejection.

Finally, the findings from both experiments highlight a key distinction: loneliness does not lead to a uniform tendency to withdraw from all social interactions. Instead, it a introduces context-sensitive embodied avoidance bias, particularly towards ambiguous or negative (neutral and angry) facial cues. These findings extend the interpretation bias findings from the Scoping Review in Chapter 1 and Facial Emotion Processing in chapter 4, demonstrating that loneliness is embodied, not just cognitive. Lonely individuals do not just perceive certain emotional cues threatening or ambiguous, they also physically withdraw and avoid which is aligned with "*The model of approach–avoidance interpersonal motivation"* by Gable and Gosnell (2013) where they suggested that while social approach and avoidance motivations are independent and separate, they also operate simultaneously.

These experiments offer several methodological and conceptual strengths that enhance the validity and interpretability of the findings. The VR paradigm validates and extends traditional lab-based findings into ecologically valid, dynamic social contexts, filling a methodological gap identified in the introduction of this chapter. Also, by including covariates, depression, social anxiety, and alexithymia, it can be argued that the avoidance effect is specific to loneliness and not just a generic marker of negative cognitive bias. Also, the findings from the pilot study highlights the necessity of validation of emotional stimuli to ensure accurate AAB measurement.

We acknowledge that, effect sizes were modest, which means that AAB in real-world interactions may involve additional factors. For instance, social behaviours might be shaped by a range of situational, emotional and relational dynamics. Moreover, while the overall pattern of findings was consistent across both experiments, some differences, such as the marginal approach trends to angry faces in Experiment 2, may reflect the inclusion of additional stimuli (the sad facial emotion), the measurement of alexithymia, or other sample-specific factors such as demographic diversity, task familiarity, or subtle procedural differences.

Overall, while traditional AAB research suggests that positive stimuli trigger approach and negative stimuli trigger avoidance, loneliness-specific AAB reveal a more complex pattern. The experiments demonstrated that loneliness changes approach-avoidance motivations. Rather than simple social withdrawal, lonely individuals show a paradoxical mix of avoidance towards ambiguous (neutral) and negative cues (angry), and a diminished approach bias for positive cues (happy faces). Thence, approach-avoidance bias might reflect the paradoxical behaviour of lonely individuals, characterised by a simultaneous desire for social connection and social avoidance caused by hypervigilance of social threat (Cacioppo & Hawkley, 2009). Consequently, this motivational conflict may perpetuate loneliness by disrupting adaptive social engagement. Moreover, the integration of findings across chapters suggests that effective interventions for loneliness should address both cognitive (interpretation) and embodied (approach-avoidance) biases, future research should explore whether modifying these biases (e.g., through immersive VR-based cognitive bias modification) can break the loneliness cycle.

CHAPTER 6

STUDY 5

Avoidance in Loneliness: Exploring Physiological and Behavioural Responses in Virtual Reality

"We are more frightened than hurt, and we suffer more from imagination than from reality." – Seneca

1. Introduction

Understanding the behavioural manifestations of loneliness became more important than ever as individuals began navigating complex social landscapes of contemporary society in a hyperconnected but emotionally fragmented digitalised world (Candiotto, 2022). Even tough loneliness is often conceptualised as an internal and subjective experience; it extends beyond emotion and shape how individuals behave through social motivations. For instance, according to "Model of Approach–Avoidance Interpersonal Motivation" proposed by Gable et al. (2006), social bonds inherently offer both incentives (e.g., intimacy) and threats (e.g., rejection) which could either lead to satisfaction or loneliness. Critically, a person's motivational focus dictates their social and emotional outcomes, meaning that a stronger avoidance predicts lower social satisfaction, and higher levels of loneliness and insecurity (Gable & Gosnell, 2013). Moreover, previous studies have found that individuals experiencing loneliness avoid social and emotional involvement, partly because they are more sensitive to anxiety triggered in social situations (Vanhalst et al., 2015; London et al., 2007). Hence, in their efforts to avoid socially challenging circumstances, lonely individuals are more prone to put greater interpersonal distance (IPD) with others (Layden et al., 2018).

1.1. The Role of Avoidance in Loneliness

Social avoidance includes three factors: *emotion, cognition,* and *behaviour* (Yuan et al., 2023), and refers to a combination of avoidant behaviours, anxiety, and other negative emotional states that individuals demonstrate in the context of social activities (Nikitin & Scotch, 2021). Previous studies showed that loneliness is a result of behavioural social avoidance (Xing et al., 2013). For instance, according to diary-based

longitudinal study conducted by Gable (2006) where participants reported on daily interactions and motivation types and avoidance goals, defined as goals focused on avoiding negative outcomes, predicted reduced responsiveness to social interactions and increased level of loneliness. Another research also reported that individuals with high levels of social avoidance are more likely to be excluded from the social groups, which leads to distress and an increased sense of loneliness (Zhang et al., 2018).

Aligned with this, in Study 2c in Chapter 3 in this thesis, the findings suggested that behavioural social avoidance significantly mediated the relationship between depression and loneliness. It indicates that avoidance stems from negative emotions and relates positively to how lonely someone perceives themselves to be, which is in line with prior research demonstrating that depression significantly impairs interpersonal functioning (Hammen, 2005; Yuan et al., 2022). For example, in a study that conducted structural equation modelling on data collected from 1,021 college students, they found that depression predicted increased level of loneliness and decreased interpersonal trust, which in turn contributed to greater social avoidance (Yuan et al., 2022).

However, despite the theoretical and correlational association between loneliness and avoidance, empirical research into the behavioural manifestations of avoidance in loneliness remains limited. As explained in Chapter 2 Scoping Review, there are only two experimental studies in the literature exploring avoidance behaviours in loneliness. Saporta et al. (2021) conducted a computerised 'Comfortable Interpersonal Distance' task, where participants pressed a key to stop an approaching virtual agent at the point, they felt most comfortable, with faster reaction indicating a preference for greater distance. They reported that chronic loneliness reinforced greater social avoidance (preference for greater interpersonal distance), while situational loneliness increased

approach motivation, suggesting that momentary feelings of loneliness can enhance the drive for social connection, unlike chronic loneliness. Moreover, lonely adults displayed greater avoidance when being approached (passive condition) compared to when they were the ones actively approaching others. Therefore, these findings underscore the importance of examining how loneliness influences not only internal emotional states but also behavioural expressions, such as interpersonal distance, a measurable indicator of avoidance in real-life interpersonal interactions.

1.2. Interpersonal Distance as an Embodied Expression of Avoidance in Loneliness

The world we are surrounded is social in nature and keeping a right distance with others is a fundamental part of functioning in a social society (Hall, 1963). Hence human spatial behaviour has been a focus of previous research in social cognitive psychology (Sorokowska et al., 2017). Interpersonal space, or *interpersonal distance (IPD)*, a space between two people, refers to *"an area with an invisible boundary surrounding a person's body, into which intruders may not come"* (Sommer, 1969, *p. 176*). IPD is essential and critical non-verbal information of individuals' social behaviour (Huang & Izumi, 2021; Hall, 1966; Hayduk, 1983). Human beings can signal aspects such as responsiveness, feelings of comfort or safety by a proper interpersonal distance (Feeney, 1999; Kaitz et al., 2004). While a smaller IPD reflects a tendency to seek intimacy, a larger IPD may signal perceived threat or a self-protective response (Coello & Cartaud, 2021; Huang & Izumi, 2021).

In Hall's (1966) description of interpersonal distance, the regulation of IPD depends on several factors, such as social norms, physical attributes and various malfunctions

and disorders (Huang & Izumi, 2021). As explained in Chapter 1, in the classical "Proxemic Theory" (Hall, 1966; Figure 70), interpersonal space is categorised into four distances, each of which reflects a different relationship between individuals (1) Intimate distance is maintained in close relationships (from 0 to 45 cm); (2) personal distance is maintained during social interactions with friends (from 45 to 120 cm); social distance is maintained during more formal interactions (from 120 to 360 cm), and (4) public distance is maintained in connections withing larger groups in society (above 360 cm).

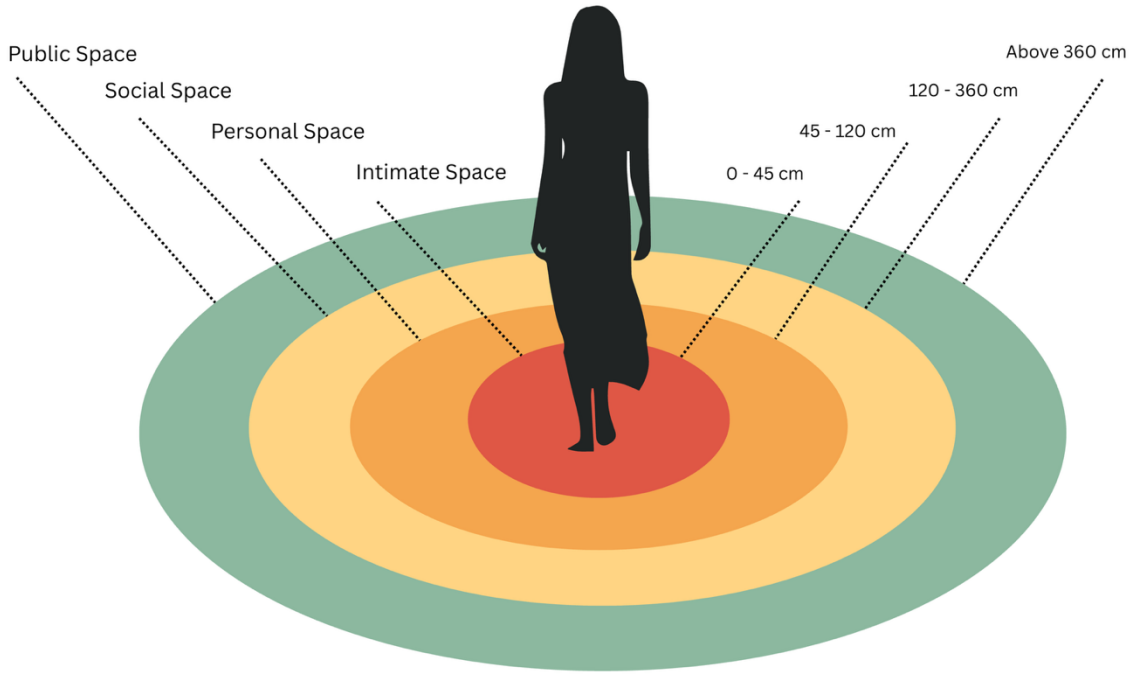


Figure 70. Interpersonal Distance Zones According to Proxemic Theory (Hall, 1966)

While the Proxemic Theory identifies the normative boundaries of interpersonal space, Cacioppo's Evolutionary Model of Loneliness suggests that loneliness influences how individuals perceive and regulate interpersonal distance (Cacioppo & Hawkley, 2009). They suggested that loneliness is associated with a set of motivational, behavioural and cognitive adjustments related to short-term self-preservation, such as

heightened vigilance to social threats, negative social expectations, fear of rejection and increased avoidance behaviours. Thus, loneliness, in fact, triggers two opposing motivations: on one hand, a drive to approach and restore social connections to support long-term survival; and on the other hand, a tendency to avoid and distance oneself from others and remain vigilant to potential social threats for short-term self-preservation. Therefore, it has been hypothesized that loneliness may also influence preferences for interpersonal distance (Cacioppo et al., 2017; Cacioppo et al., 2015). For instance, in a survey-based study by Layden et al. (2018) showed that loneliness predicted larger interpersonal distance within intimate space. Moreover, a field study in which they obtained naturalistic and stop-distance measures of interpersonal distance reported that those who experience social isolation preferred larger interpersonal distance (Gifford & Sacilotto, 1993). While behavioural findings suggest that loneliness shapes how individuals regulate proximity to others, less is known about the underlying physiological mechanisms, such as heart rate variability, that may support these avoidance-oriented responses.

1.3. Heart Rate Variability as a Physiological Marker of Avoidance

Heart Rate Variability (HRV) is a physiological marker of top-down self-regulation, reflecting the functional connection between neural control systems (e.g. prefrontal cortex) and cardiac activity and it reflects variation in time intervals between consecutive heartbeats (Holzman & Bridgett, 2017; Kemp et al., 2012). More specifically, HRV reflects the dynamic interaction between the parasympathetic and sympathetic activity where increased HRV indicates greater flexibility and adaptive capacity which is a healthy Autonomic Nervous System (ANS), and decreased HRV indicates autonomic

inflexibility (Neyer et al., 2022). The Neurovisceral Integration Model (NIM) suggests that HRV is a key physiological indicator of the brain's ability to regulate emotional and behavioural responses (Williams et al., 2015).

Recent research highlights HRV as a physiological correlate of interpersonal functioning and avoidance, suggesting that social engagement systems can help regulating the autonomic nervous system by reducing sympathetic overreaction, which supports healthier HRV (Kim et al., 2024; Smith et al., 2019). For instance, Kim et al. (2024) found that individuals with higher levels of social avoidance and interpersonal distress demonstrated significantly lower HRV, supporting that HRV reflects not only autonomic regulation but also interpersonal functioning where lower vagal tone may signal reduced capacity for social approach and adaptive engagement in social interactions. Similarly, Smith et al. (2020) argued that vagally mediated HRV functions as a biosocial marker of social engagement capacity, with higher HRV indicating increased ability to connect with others.

Furthermore, Porges (2022) presented a polyvagal perspective, arguing that vagally mediated HRV is a key indicator of the autonomic nervous system's capacity to support social engagement, emotional regulation, and physiological resilience, linking safety cues with adaptive neural and cardiac function. Aligned with this, Smith and Pollak (2022) found that lonely adults with higher parasympathetic nervous system (PNS) activity showed increased motivation to approach both rewarding and aversive stimuli, suggesting a heightened engagement with socially relevant cues regardless of valence.

Overall, these findings position HRV as a critical physiological marker of avoidance behaviours and social adaptability which are both central to loneliness. However,

beyond physiological regulation, social engagement is contingent upon social evaluations, particularly perceptions of interpersonal trust.

1.4. Interpersonal Trust in Loneliness: A Buffer Against Avoidance

Trust is a key factor in social relationships, and it is inseparable from interpersonal communication (Tianqi & Jinhao, 2024). The development of positive social bonds typically relies on cooperation, while non-cooperative behaviours tend to provoke avoidance or even punishment (Henrich & Henrich, 2006). However, during initial encounters without prior information about others' likelihood to reciprocate, quick judgments are required about trustworthiness to form a new relationships (Lieberz et al., 2021).

Previous research suggested that loneliness is associated with lower levels of trust. For instance, as mentioned in Chapter 3 exploring predictors of loneliness, Rotenberg (1994) found a negative correlation between loneliness and generalised trust beliefs where lonely adolescents demonstrated less trusting behaviours in the Prisoner's Dilemma Game. Their findings were supported by another study using the same game where they reported that higher loneliness was significantly associated with lower trust beliefs and less trusting behaviours among peers during adolescence (Rotenberg et al., 2004). Similarly, Qualter et al. (2009) also found that interpersonal distrust had a strong and direct effect on social loneliness in a cross-sectional survey study among university students.

Moreover, emerging evidence suggests that loneliness is associated with alterations in the neural and cognitive processes that support interpersonal trust. For instance, Bellucci and Park (2023) used a behavioural trust-learning task combined with

computational modelling and functional neuroimaging with fMRI to investigate how lonely individuals update trustworthiness impressions based on positive and negative social feedback. They found that loneliness was associated with biased trust formation where negative social information was weighted more strongly than positive information, leading to persistently negative trustworthiness judgements. Earlier experimental research from Bellucci et al. (2017) also found that lonely individuals demonstrated reduced willingness to trust others, specifically, they relied less on expectations of partner reciprocity in economic trust games, leading to lower trust behaviour compared with non-lonely individuals. Similarly, Lieberz et al. (2021) also reported that loneliness is associated with reduced interpersonal trust at behavioural, hormonal, and neural levels, reflecting compromised integration of trust-related information that promotes social distance and reinforces avoidance in social interactions. These findings were supported by a recent research reporting that lonely individuals demonstrate decreased level of trust and related neural responses, potentially reinforcing social withdrawal and limiting the restorative potential of social interactions (Bellucci et al., 2025).

While previous studies have examined self-reported trust in relation to loneliness, the role of behavioural indicators of interpersonal trust in terms of avoidance, such as preferred interpersonal distance, remains largely unexplored. Therefore, the present study explored how loneliness influences behavioural and physiological indices of avoidance, measured with IPD and HRV, across social and non-social virtual reality contexts, while accounting for depression, social anxiety, avoidance tendencies, and interpersonal trust.

1.5. Research Questions

RQ1. Is loneliness associated with physiological responses, as indexed by HRV during non-social observation, after controlling for depression, social anxiety, and non-social avoidance?

RQ2. Is loneliness associated with social dynamic preferences (alone vs group) in a social virtual environment and to what extent are these associations accounted for by depression, social anxiety, trust, and behavioural avoidance?

RQ3. Is loneliness associated with (a) HRV level and (b) IPD during social observation, when controlling for depression, social anxiety, trust, and behavioural social avoidance?

RQ4. Is loneliness associated with (a) HRV level and (b) IPD during social engagement, when controlling for depression, social anxiety, trust, and behavioural social avoidance?

RQ5. Do associations between loneliness and (a) HRV and (b) IPD differ between social observation and social engagement contexts?

2. Methods

2.1. Participants

A priori power analysis was conducted using G*Power 3.1 to determine the required sample size for a linear multiple regression analysis (fixed model, R^2 increase). Assuming a medium effect size ($f^2 = 0.15$), an alpha level of 0.05, and a desired statistical power of 0.80, the analysis indicated that a sample size of 55 participants was required. The model included five predictors (loneliness, depression, social anxiety, avoidance and trust), with the test focusing on the incremental contribution of one additional predictor. Although 55 participants were initially recruited, data from 2 individuals were

excluded due to extreme outlier values. Therefore, a total of 53 participants (30 females, 56.6%, M_{age} = 34.77, *SD* = 12.83, ranged from 18 to 74) were analysed in this study. Demographic characteristics of participants and scale scores are presented in Table 39.

Table 39. Participant Demographics and Descriptive Statistics (*N* = 53)

Age Mean (+/- SD)	34.77 (12.83)	***Employment***	
Sex		*Student*	26 (49.1%)
Female	30 (56.6%)	*Full-time employed*	9 (17%)
Male	23 (43.4%)	*Part-time employed*	8 (15.1%)
Education level		*Homemaker*	4 (7.5%)
Highschool	19 (35.8%)	*Retired*	4 (7.5%)
Bachelor's degree	9 (17%)	*Unemployed*	2 (3.8%)
Master's degree	18 (34%)	***Ethnicity***	
PhD	7 (13.2%)	*White*	35 (66%)
Relationship status		*Black or Black British African*	4 (7.5%)
Single	25 (47.2%)	*Asian or Asian British Indian*	3 (5.7%)
In a relationship	16 (30.2%)	*Mixed – White and Black*	4 (7.5%)
Married	10 (18.9%)	*Chinese*	5 (9.4%)
Separated	2 (3.8%)	*Arab*	4 (7.3%)
Living condition		***Scales***	
Alone	13 (24.5%)	*Loneliness Mean (+/- SD)*	43.9 (10.1)
With parents	6 (11.3%)	*Depression Mean (+/- SD)*	14.11 (4.3)
With other family members	6 (11.3%)	*Social Anxiety Mean (+/- SD)*	8.6 (5.15)
With friends or shared	11 (24.5%)	*Avoidance Mean (+/- SD)*	68.7 (20.5)
With partner/husband/wife	17 (32.1%)	*Trust Mean (+/- SD)*	3.5 (0.6)

2.2. Measures

Demographic variables: All participants answered sociodemographic questions such as age, biological sex, education level, relationship status, living condition, employment and ethnicity.

Loneliness: The UCLA Loneliness Scale (Version 3; Russell, 1996) was used to measure participants' loneliness levels. The instrument consists of 20 items (e.g., "*How often do you feel left out?*"). Responses vary on a scale from 1 (never) to 4 (often) and total score ranges from 20 to 80. Internal consistency in this study sample was excellent (α= .94).

Depression: The Center for Epidemiologic Studies Short Depression Scale (Ces-D-R-10; Radloff, 1977), a 10-item measure was used to assess depressive symptomology. Items are rated on a four-point scale (*from 0=rarely or none of the time to 3=most or all the time*). Total scores range from 0 to 30, with higher scores representing a more depressed mood. Internal consistency in this study sample was good (α= .88).

Social anxiety: Social Interaction Anxiety-6 (SIAS-6; Peters et al., 2012) was used to measure participants' level of social anxiety regarding initiating and maintaining social connections. The items were measured on a 5-point Likert scale (*from 0=Not at all to 5=Extremely*). Total scores range from 0 to 24 with recommended cut-off score 7 or higher (Zsio et al., 2021). Internal consistency in this study sample was excellent (α= .92).

Avoidance: Cognitive Behavior Avoidance Scale (CBAS; Ottenbreit & Dobson, 2004) is a 31-item multi-dimensional measure of avoidance with four factors including *behavioural social and non-social, cognitive social and non-social avoidance*. Respondents indicated how true the mentioned strategies for them using a 5-point scale (*1= not at all true for me to 5= extremely true for me).* The items are summarised to provide an overall score that ranges from 31 to 155 with a score of 53 is suggested as the optimum cut-off point (Barajas et al., 2017). Higher scores indicate more avoidance. Internal consistency in this sample was excellent (α= .96).

Trust: The General Trust Scale (GTS; Yamagishi & Yamagishi, 1994) was used to measure participants' levels of trust in terms of beliefs about honesty and trustworthiness of others, in general. GTS is a 6-item questionnaire on a 5-point scale ranging from 1 (*Strongly disagree*) to 5 (*Strongly agree*). The score for each item is averaged together to form a continuous measure of generalised trust. Internal consistency in this sample was excellent (α= .93).

Virtual Reality Immersion and Presence: To assess participants' subjective experience of immersion and presence in the virtual environment, the Igroup Presence Questionnaire (IPQ; Schubert, Friedmann, & Regenbrecht, 2001) was administered. The IPQ is a widely used and psychometrically validated self-report instrument developed to measure presence as a psychological construct distinct from technological immersion. It includes three subscales with 14 items in total representing three theoretically grounded components of presence: *Spatial Presence* (6 items; Slater & Usoh, 1994), *Involvement* (4 items; Witmer & Singer, 1994), and *Experienced Realism* (3 items; Hendrix, 1994; Witmer & Singer, 1994). In the present study, participants rated each item on a 7-point Likert scale, with higher scores indicating greater presence.

2.3. Materials

Virtual Reality: The study was conducted in a VR lab using the HTC Vive Pro Eye headset (HTC Corporation, 2019), offering 1440 × 1600 resolution per eye, and a 110° field of view. Head movement was tracked in real time across X (left-right), Y (up-down), and Z (forward-backward) axes, and audio was delivered via built-in headphones. The VR environment was created in Unity and run on a high-performance PC with four SteamVR Base Station 2.0 sensors recording head position at ~15 Hz. Participants

entered a realistic pub-style setting (Figure 71), where virtual agents were placed around a table. Agent positions were randomised across trials and participants using angular coordinates (0°–360°), which specify positions around a central point in a circular layout (e.g., placing virtual agents at varying angles relative to the participant), to prevent habituation and control for positional bias.

Figure 71. Overhead View of the Virtual Pub Environment with the Virtual Agents (angular coordinates: 0°–360°)

Psychophysiological measures: Heart rate variability (HRV) was used as a measure to assess participants' physiological responses to different social virtual environments. HRV data were collected using the chest-strap device Polar H10 heart rate sensor (Polar Electro Oy), a validated and reliable tool for capturing interbeat intervals (IBIs) with high temporal precision. Its validity for psychophysiological research, including emotional and stress-related responses, has been supported by previous studies (e.g., Schaffarczyk et al., 2022), making it an appropriate instrument for monitoring physiological engagement in immersive virtual contexts.

2.4. Procedure

Figure 72 provides demonstration of the virtual reality experimental setup at the VR lab at UEA and Figure 73 provides an overview of the experimental procedure, outlining the three-phase structure of the study, including recruitment, pre- and post-VR assessments, a familiarisation session, and the "Virtual Pub Social Interaction Paradigm" designed to assess behavioural and physiological responses associated with loneliness. In Phase 1, participants were screened for inclusion criteria which were fluent in English and aged over 18 years old. Individuals with motion sickness were excluded. In Phase 2, upon arrival to the VR lab, participants were asked to complete an online Qualtrics survey. Next, participants were fitted with a Polar chest band HRV monitor. The HRV graph was monitored for signal quality before beginning the experiment. Participants were informed that the study involved four short VR trials lasting approximately 6-8 minutes total. The boundary system, a virtual wall, within the VR environment was used to ensure physical safety, and researchers were prepared to intervene verbally if needed. After each trial, participants returned to the original starting point (a yellow line in the VR space), guided by auditory cues (e.g., a bell sound). In Phase 3, participants completed a final brief questionnaire assessing their sense of presence and immersion within the VR environment. Afterwards, they were reimbursed with £5 or SONA credits for participation and provided debriefing sheet.

Figure 72. Demonstration of the Virtual Reality Experimental Setup (University of East Anglia)

Note: The photo was taken at the VR Lab, University of East Anglia, the UK. From left to right: Ceyda Kiyak (PhD researcher); Dr Sara Bengtsson (Lead Supervisor), Dr Gareth Edwards (Co-supervisor), and Richard Humphrey (VR Technician), who kindly modelled the setup for illustrative purposes with the courtesy and support of the supervisory team.

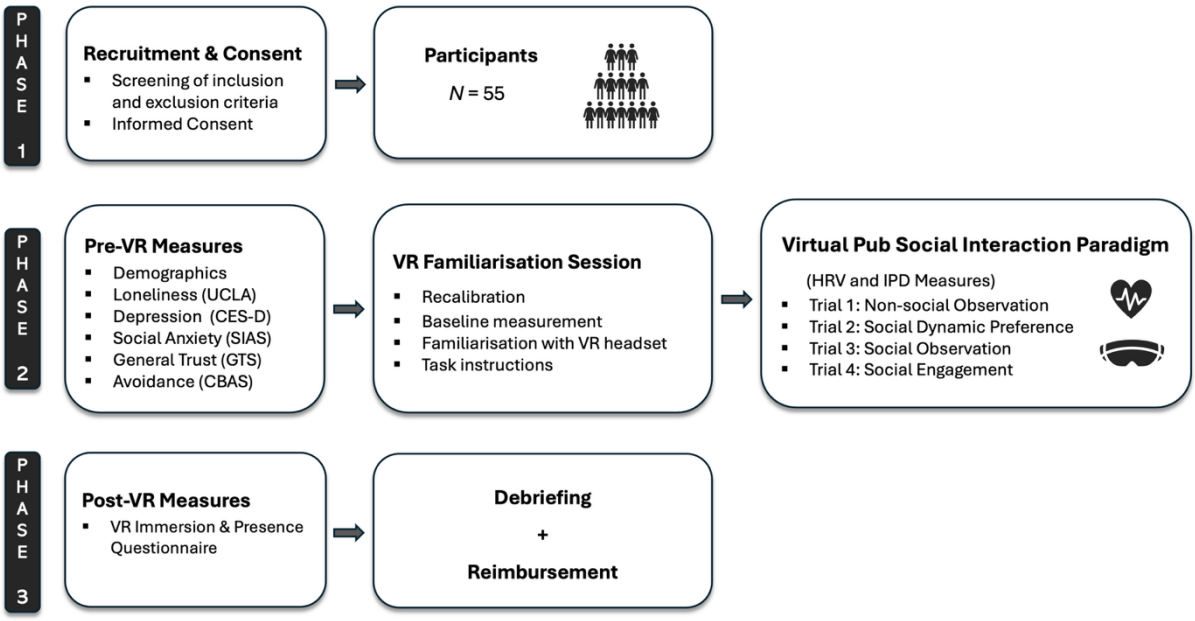


Figure 73. Overview of the Experimental Procedure and Virtual Reality Social Interaction Paradigm

Trial 1 - Non-social Observation: Participants entered a virtual pub with background chatter and jazz music. They were instructed to explore the environment for 60 seconds while HRV was continuously monitored to establish a baseline measure of physiological responses in a non-social context where there were no virtual agents.

Trial 2 - Social dynamic Preference: Participants were asked to select a table to stand at within the virtual pub environment. On the left side of the room, they saw four virtual agents, while on the right side, there was a female virtual agent standing alone by another table (Figure 74). Participants were instructed to choose where to position themselves, on the left with the group vs on the right with the single agent.

Figure 74. Trial 2 – Social Dynamic Preference (left: group of agents vs right: a single agent)

Trial 3 – Social Observation: Participants remained in the same virtual pub, where four virtual agents (2 male and 2 female) were standing around a table on the left side of the pub having a conversation. Participants were instructed to approach the group of virtual agents and listen to what they were talking about. Throughout this trial, their HRV and IPD was continuously measured.

Trial 4 - Social Engagement: In this trial, participants were asked to approach to the group of agents again, but to engage with verbally or non-verbally this time. Their HRV and IPD were monitored to measure their reactions during this natural social approach.

2.5. Data Processing

IPD Data Computation: IPD was operationalised as the minimum forward distance (in meters) between the participant and the centre of the virtual table where the agents were located. Head position tracking data on the Z-axis (forward–backward movement)

was used, starting from an initial distance of 6 meters. To ensure that the analysis reflected active social engagement rather than passive presence in the environment, only data frames where participants' avatars were located within a 3-meter radius of the central table, the primary site of social interaction, were retained. This spatial threshold was used to include only those moments where participants were physically close enough to engage with the virtual agents, based on typical interpersonal distance norms in social contexts. Additionally, head orientation data was used to confirm that participants were actively looking toward the group; only frames where the yaw angle was within 330°–360° or 0°–30° were included, indicating gaze direction toward the virtual agents. For each trial, the minimum IPD was calculated based on the subset of frames where participants were detected within 3 meters of the interaction table, a proximity threshold used to define active social engagement. These frames have been filtered and included, ensuring that the recorded IPD reflected moments of potential or actual social interaction.

HRV Data Computation: HRV was calculated using the mean of interbeat interval values during a 60-second window (16–76s) of Trial 1 (Figure 75), excluding the initial 15 seconds to reduce physiological noise and sensor drift (Shaffer & Ginsberg, 2017). This window was selected for consistency across trials and to optimize internal validity. Implausible values (<0 or >180 ms) were removed. Participants 44, 45, and 48 were excluded due to missing or corrupted HRV data. For Trial 3 and 4, HRV was quantified by calculating the mean of interbeat interval (IBI) values recorded during the trial duration, providing an average HRV measure that reflects participants' physiological arousal in response to different social contexts.

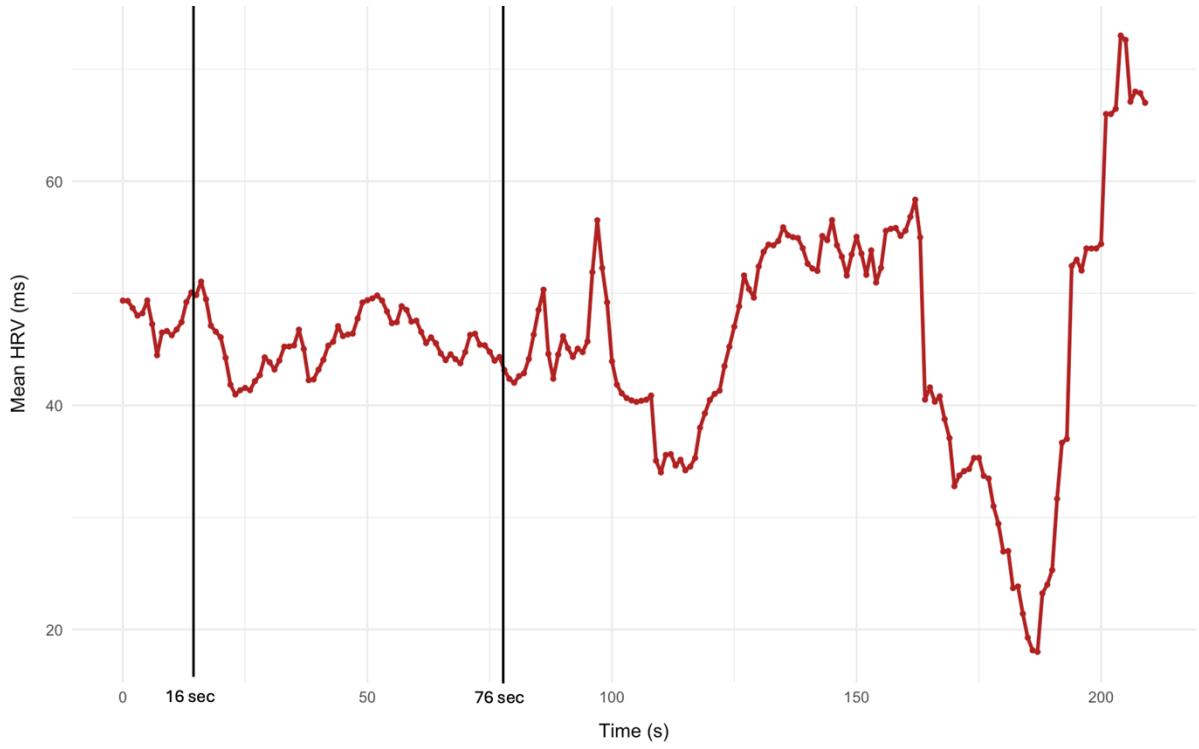


Figure 75. Mean Heart Rate Variability (HRV) Over Time During Trial 1

Note: Mean HRV (in milliseconds) is plotted across the full duration of the VR task. The orange vertical lines indicate key transitions: the beginning of the first social stimulus at 16 seconds and a task-phase shift at 76 seconds. HRV initially decreases, followed by fluctuations, with a marked drop around 100–150 seconds, and a recovery toward the end of the task.

2.6. Design

The study employed a multi-method analytic strategy across four VR trials to examine the relationship between loneliness, behavioural and physiological responses. For Trial 1, a multiple linear regression was used to test whether loneliness is associated with HRV, controlling for depression, social anxiety, and non-social avoidance. For Trial 2, logistic regression was run to assess whether loneliness predicted the binary choice of social preference (alone vs group), with depression, social anxiety, trust, and behavioural avoidance included as covariates. For Trial 3, two multiple linear regression models examined the influence of loneliness on (1) HRV and (2) IPD, controlling for depression, social anxiety, trust, and behavioural social avoidance. For Trial 4, similar

to Trial 3, multiple linear regression models were used to examine the influence of loneliness on HRV and IPD using the same covariates. Finally, for Trial 3 and 4, exploratory linear mixed model (LMM) was conducted to examine whether the relationship between loneliness and outcome variables (HRV and IPD) differed by trial type (Trial 3: observation vs. Trial 4: engagement), accounting for within-subject variability and key covariates.

Although the Igroup Presence Questionnaire (IPQ) was initially considered for assessing immersion and presence in the virtual environment, it was ultimately excluded due to concerns about statistical power and model complexity, as the number of covariates relative to the available sample size would have compromised the reliability of the analyses.

2.7. Ethics

The study was approved by the UEA PSY ethics committee (ETH2324-1222). In compliance with open science principles, the study was registered on OSF (https://osf.io/dtq76). All participants were treated following APA ethical guidelines (American Psychological Association, 2017). Also, the study was conducted in accordance with the principles expressed in the Declaration of Helsinki (World Medical Association, 2013). Moreover, as the research involve human participation, the Research Ethics Code of Practice was followed.

3. Results

3.1. Physiological Responses to a Non-Social Observation: Behavioural and Cognitive Non-Social Avoidance in Loneliness

A multiple linear regression was conducted to examine whether loneliness, depression, social anxiety, behavioural non-social avoidance and cognitive non-social avoidance predicted heart rate variability (HRV) during non-social virtual environment observation. The overall model was not statistically significant, F (5, 46) = 1.46, p = .221, explaining 13.7% of the variance in HRV (R^2 = .137, adjusted R^2 = .043).

Loneliness demonstrated a *marginally* significant *negative* association with HRV (Table 40), B = –0.31, SE = 0.17, t = –1.89, p = .066, suggesting that individuals reporting higher loneliness demonstrated lower HRV (Figure 76). Depression, social anxiety, behavioural non-social avoidance and cognitive non-social avoidance were not significantly associated with HRV.

Table 40. Multiple Linear Regression Predicting HRV During Non-Social Observation (Trial 1)

Predictor	Estimate (B)	SE	t	95% CI (Lower, Upper)	*p*
Intercept: HRV	56.34	10.07	5.59	[36.61, 76.07]	**< .001***
Loneliness	–0.31	0.17	–1.89	[–0.64, 0.01]	.066†
Depression	–0.45	0.45	–1.01	[–1.33, 0.43]	.320
Social Anxiety	0.34	0.32	1.06	[–0.29, 0.96]	.293
Behavioural Non-Social	0.31	0.53	0.58	[–0.73, 1.36]	.564
Cognitive Non-Social	0.09	0.26	0.33	[–0.43, 0.60]	.744

Note: B = unstandardized regression coefficient; SE = standard error; CI = confidence interval. Significant at p < .001. †Trend-level significance (p < .10).

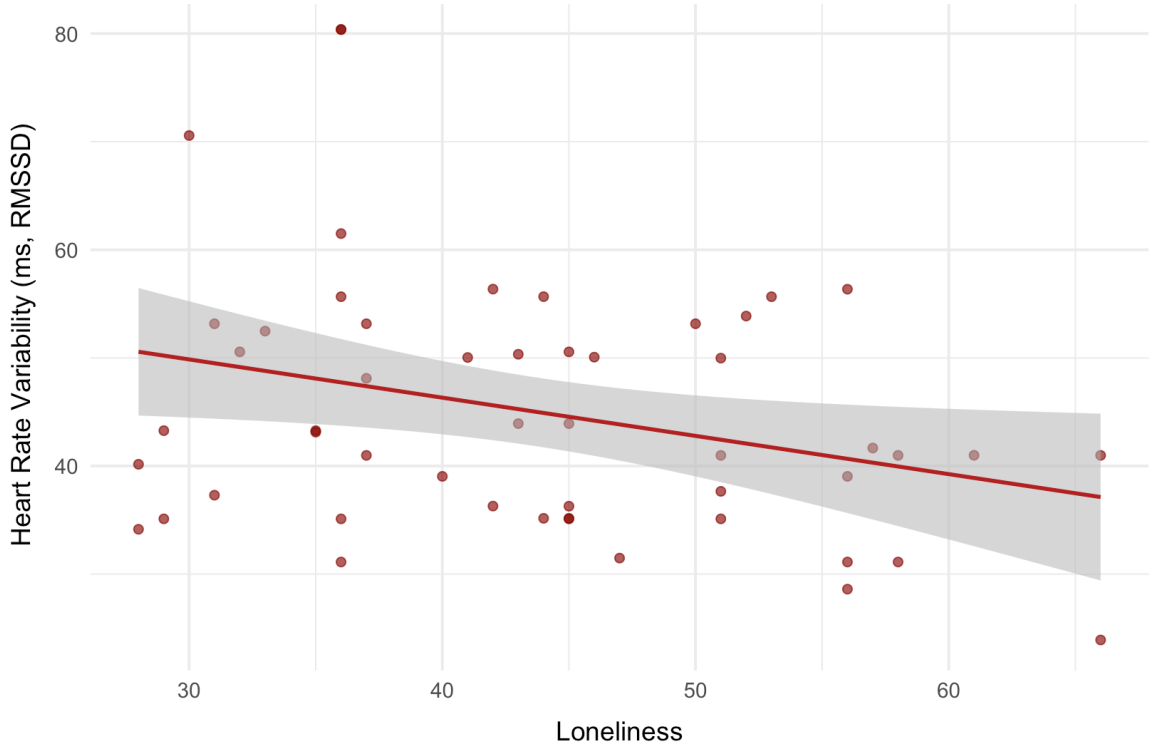


Figure 76. Association Between Loneliness and HRV During Non-Social Virtual Environment Observation

Note. The scatterplot illustrates the negative association between loneliness and heart rate variability (RMSSD) during the non-social VR trial. The shaded area represents the 95% confidence interval around the regression line. Participants with higher loneliness levels tended to show lower HRV during non-social and agent-free exploration.

3.2. Social Dynamic Preference in VR: Social Avoidance in Loneliness

A binary logistic regression was conducted to examine the association between loneliness, depression, social anxiety, trust and behavioural avoidance with the likelihood of choosing alone virtual agent vs group of virtual agents. The overall model was statistically significant, χ^2 (5) = 12.06, p = .034. The model explained 23.4% of the variance in choice (Nagelkerke R^2 = .234) and correctly classified 78.4% of cases.

As shown on Table 41, loneliness was significantly associated with increased odds of choosing alone virtual agent B = 0.25, SE = 0.13, z = 1.97, p = .048, OR = 1.28. This indicates that for each one-point increase in loneliness, the odds of choosing alone

virtual agent increased by 28%. *Social anxiety* was also positively associated with choosing alone virtual agent, B = 0.38, SE = 0.18, z = 2.08, p = .037, OR = 1.46, as did *behavioural avoidance*, B = 0.83, SE = 0.38, z = 2.19, p = .028, OR = 2.30. *Trust* showed a strong association with choosing alone virtual agent, B = 3.58, SE = 1.62, z = 2.22, p = .027, OR = 35.9. *Depression* was not significantly associated with social dynamic preference, B = -0.27, SE = 0.21, z = -1.27, p = .205, OR = 0.77.

Table 41. Binary Logistic Regression Predicting Likelihood of Choosing Social Dynamic (Trial 2)

Predictor	Estimate (B)	SE	z	*p*	95% CI Lower	95% CI Upper	OR	OR 95% CI Lower	OR 95% CI Upper
Intercept	-31.30	13.00	-2.41	**0.016***	-65.60	-6.00	2.66e-14	4.33e-29	0.002
Loneliness	0.248	0.126	1.97	**0.048***	0.062	0.569	1.28	1.06	1.77
Depression	-0.268	0.212	-1.27	0.205	-0.813	0.277	0.765	0.444	1.32
Social Anxiety	0.379	0.182	2.08	**0.037***	0.102	0.869	1.46	1.11	2.38
Trust	3.58	1.62	2.22	**0.027***	1.01	7.65	35.9	2.75	2090
Behavioural Avoidance	0.831	0.379	2.19	**0.028***	0.303	1.85	2.30	1.35	6.36

Note. OR = Odds Ratio; CI = Confidence Interval.

3.3. Social Observation: Physiological Responses and Interpersonal Distance in Loneliness

3.3.1. Loneliness and Heart Rate Variability During Social Observation

A multiple linear regression was conducted to examine the association between loneliness and HRV during social observation, while controlling for depression, social anxiety, trust, and behavioural social avoidance. The model was not statistically significant, F (5, 46) = 1.98, p = .099, explaining approximately 17.7% of the variance in HRV (R^2 = .18, adjusted R^2 = .09).

As shown in Table 42, loneliness was not significantly associated with HRV, β = −0.59, t (46) = −1.88, p = .066, however, the *marginal* negative coefficient and the scatter

plot suggest a trend where higher loneliness may be associated with lower HRV (Figure 77). Conversely, social anxiety also showed a marginally significant positive association with HRV, $\beta = 1.23$, $t\ (46) = 1.99$, $p = .052$, meaning that participants with higher social anxiety tended to have higher HRV, unlike loneliness. Depression, trust, and behavioural social avoidance were not significantly associated with HRV.

Table 42. Multiple Linear Regression Predicting HRV During Social Observation (Trial 3)

Predictor	Estimate (B)	SE	t	95% CI (Lower, Upper)	*p*
(Intercept)	93.93	28.63	3.28	[37.82, 150.05]	**.002****
Loneliness	-0.59	0.31	-1.88	[-1.20, 0.02]	.066†
Depression	-0.37	0.82	-0.45	[-1.99, 1.24]	.654
Social Anxiety	1.23	0.62	1.99	[0.02, 2.45]	.052†
Trust	-8.66	6.02	-1.44	[-20.47, 3.15]	.157
Behavioural Social Avoidance	0.15	0.55	0.27	[-0.93, 1.22]	.790

*Note. † $p > .05$, *** $p < .001$*

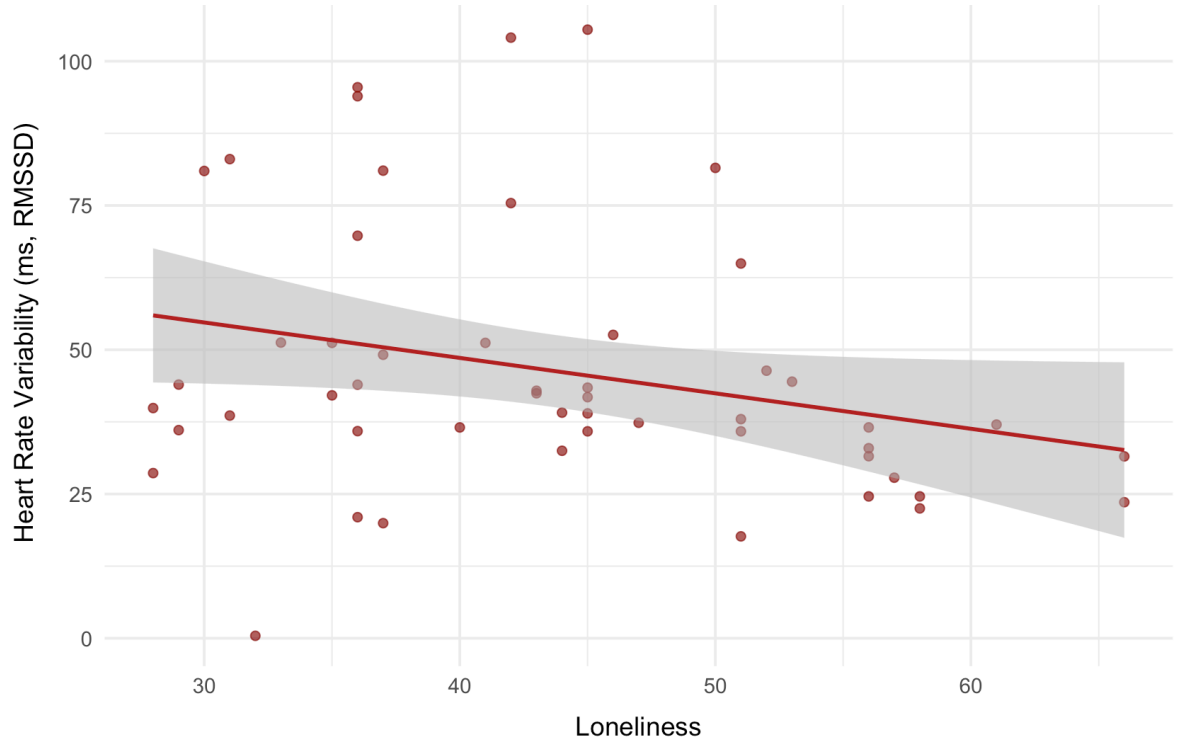


Figure 77. Association Between Loneliness and HRV during Social Observation (Trial 3)

Note. The shaded area represents the 95% confidence interval around the regression line. Participants with higher loneliness scores tended to have lower HRV during social observation, indicating a negative association between loneliness and autonomic regulation in this context.

3.3.2. Loneliness and Interpersonal Distance During Social Observation

A multiple linear regression was conducted to examine the association between loneliness and interpersonal distance (IPD) during social observation, controlling for depression, social anxiety, trust, and behavioural social avoidance. The model was statistically significant, F (5, 46) = 2.63, p = .036, accounting for 22% of the variance in IPD (Adjusted R^2 = .14).

Loneliness was significantly associated with greater IPD (B = 0.017, SE = 0.008, t = 2.18, p = .034), indicating that individuals reporting higher loneliness maintained slightly more distance from the virtual agents (Table 43). Social anxiety was also significantly associated with greater IPD (B = 0.034, SE = 0.016, t = 2.14, p = .038), with higher social anxiety associated with greater distance. Depression, trust and behavioural social avoidance were not significant significantly associated with IPD during social observation.

Table 43. Multiple Linear Regression Predicting IPD During Social Observation (Trial 3)

Predictor	Estimate (B)	SE	t	95% CI (Lower, Upper)	*p*
(Intercept)	1.0139	0.7216	1.405	[−0.4003, 2.4282]	0.166
Loneliness	0.0171	0.0079	2.181	[0.0017, 0.0325]	**0.034***
Depression	-0.0052	0.0208	-0.250	[−0.0461, 0.0356]	0.803
Social Anxiety	0.0335	0.0157	2.135	[0.0028, 0.0643]	**0.038***
Trust	-0.2689	0.1520	-1.769	[−0.5668, 0.0290]	0.083†
Behavioural Social Avoidance	0.0030	0.0138	0.216	[−0.0241, 0.0301]	0.830

Note. B = unstandardized regression coefficient; SE = standard error; CI = confidence interval; IPD = interpersonal distance. All predictors were entered simultaneously. † p < .10. * p < .05.

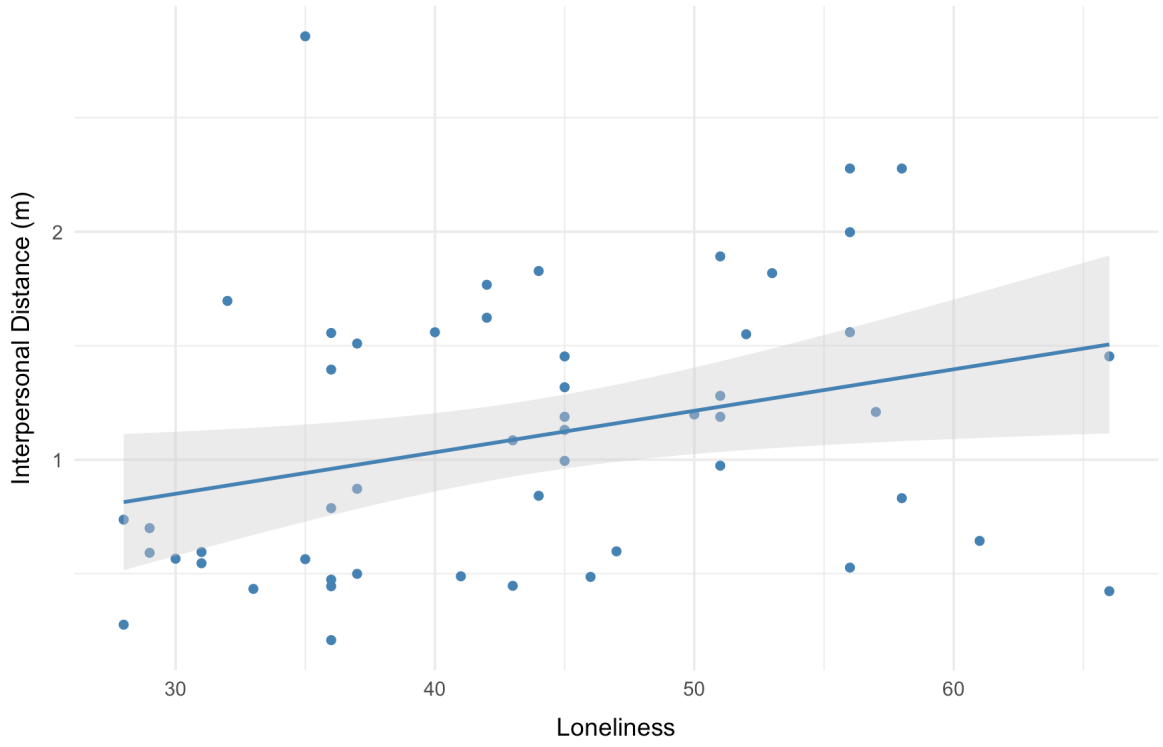


Figure 78. Association Between Loneliness and Interpersonal Distance during Social Observation (Trial 3)

Note. Each point represents an individual participant; the line shows the fitted linear regression with 95% confidence intervals. Participants with higher loneliness scores tended to maintain greater interpersonal distance during social observation.

3.4. Social Engagement: Physiological Responses and Interpersonal Distance in Loneliness

3.4.1. Loneliness and Heart Rate Variability During Social Engagement

A multiple linear regression was conducted to examine the association between loneliness, depression, social anxiety, trust, and behavioural social avoidance with HRV during Trial 4 where participants engaged in the group conversation with the virtual agents. The overall model was statistically significant, F (5, 46) = 2.65, p = .035, explaining approximately 22.4% of the variance in HRV (adjusted R^2 = .14).

Higher loneliness was associated with lower HRV, B = −0.52, SE = 0.20, t = −2.59, p = .013, indicating that higher levels of loneliness were associated with reduced HRV,

suggesting lonelier individuals demonstrated reduced parasympathetic activity during social engagement (Table 44 and Figure 79). Conversely, higher social anxiety was associated with higher HRV, $B = 0.96$, $SE = 0.40$, $t = 2.41$, $p = .020$. Depression, trust, and behavioural social avoidance were not significantly associated HRV (all $ps > .36$).

Table 44. Multiple Linear Regression Predicting HRV During Social Engagement (Trial 4)

Predictor	Estimate (B)	SE	t	95% CI (Lower, Upper)	*p*
(Intercept)	53.26	18.41	2.89	[17.19, 89.34]	**.006****
Loneliness	−0.52	0.20	−2.59	[−0.91, −0.13]	**.013***
Depression	−0.47	0.53	−0.90	[−1.51, 0.56]	.375
Social Anxiety	0.96	0.40	2.41	[0.18, 1.74]	**.020***
Trust	1.05	3.87	0.27	[−6.54, 8.64]	.787
Behavioural Social Avoidance	0.33	0.35	0.92	[−0.36, 1.01]	.360

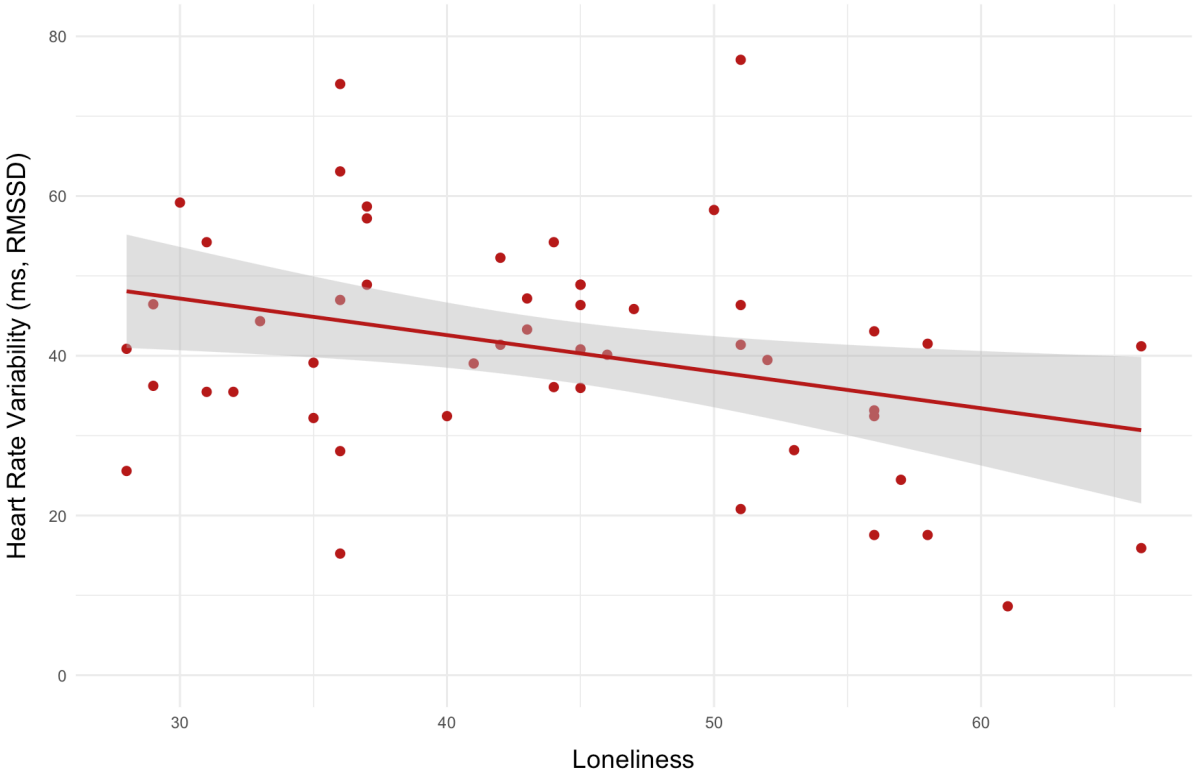


Figure 79. Association Between Loneliness and HRV during Social Engagement (Trial 4)

Note. Higher loneliness was associated with lower HRV during social engagement, controlling for depression, social anxiety, trust, and behavioural social avoidance

3.4.2. Loneliness and Interpersonal Distance During Social Engagement

A multiple linear regression was conducted to examine the association between loneliness and interpersonal distance (IPD) during social engagement, controlling for depression, social anxiety, trust, and behavioural social avoidance. The overall model was not statistically significant, F (5, 46) = 1.19, p = .329, and explained approximately 11% of the variance in IPD (R^2 = .114, Adjusted R^2 = .018).

Loneliness was not significantly associated with IPD (β = 0.001, p = .811), nor were depression, social anxiety, or behavioural avoidance (ps > .05; Table 45; Figure 80). However, trust was negatively associated with IPD (β = -0.218, p = .026), such that participants with lower interpersonal trust tended to maintain a greater interpersonal distance.

Table 45. Multiple Linear Regression Predicting IPD During Social Engagement (Trial 4)

Predictor	Estimate (B)	SE	t	95% CI (Lower, Upper)	*p*
(Intercept)	1.52	0.45	3.39	[0.64, 2.40]	**.001****
Loneliness	0.001	0.005	0.24	[–0.008, 0.011]	.811
Depression	–0.008	0.013	–0.65	[–0.034, 0.017]	.521
Social Anxiety	0.004	0.010	0.39	[–0.015, 0.023]	.700
Trust	–0.22	0.095	–2.30	[–0.404, –0.033]	**.026***
Behavioural Social Avoidance	–0.004	0.009	–0.44	[–0.024, 0.030]	.662

Note. B = unstandardized regression coefficient; SE = standard error; CI = confidence interval; IPD = interpersonal distance. All predictors were entered simultaneously. † p < .10. * p < .05.

As illustrated in Figure 80, unlike Trial 3: Social Observation, there was no statistically significant association between loneliness and interpersonal distance during social engagement, with the fitted regression line remaining relatively flat across levels of loneliness.

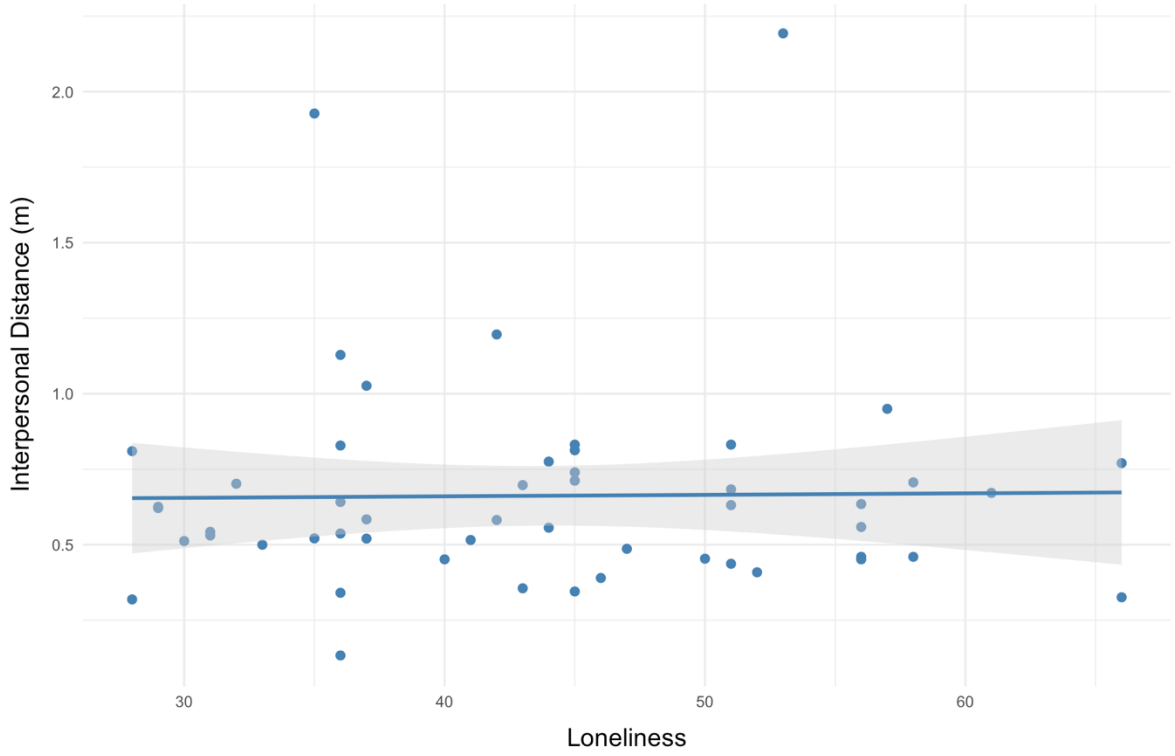


Figure 80. Association Between Loneliness and IPD during Social Engagement (Trial 4)

3.5. Exploratory Analysis of Trial 3 vs Trial 4: Changes in Physiological Responses and Interpersonal Distance in

3.5.1. Loneliness and Heart Rate Variability: Social Observation vs Social Engagement

A Linear Mixed Model (LMM) was conducted to examine the effects of trial (Trial 3: Observation vs. Trial 4: Engagement), loneliness, and their interaction on mean HRV, while controlling for depression, social anxiety, trust, and behavioural social avoidance. The model included a random intercept for participants to account for repeated measures. The model explained 18.5% of the variance in HRV via fixed effects (*marginal* R^2 = .185), and 59.98% of the variance when accounting for both fixed and random effects (*conditional* R^2 = .600). The model's REML criterion at convergence was 868.5, indicating adequate model fit.

Loneliness was negatively associated with HRV, $B = -0.59$, $SE = 0.26$, t (71.33) = –2.28, $p = .025$, indicating that participants with higher loneliness demonstrated lower HRV across trials (Table 46). Meanwhile, social anxiety was positively associated with HRV, $B = 1.19$, $SE = 0.45$, t (46.10) = 2.64, $p = .011$. Depression, trust, and behavioural social avoidance were not significantly associated with HRV (ps > .27). The main effect of trial was not significant, $B = -8.91$, $SE = 11.4$, t (49.9) = –0.78, $p = .438$, and the trial × loneliness interaction was not significant either, $B = 0.10$, $SE = 0.25$, t (49.9) = 0.38, $p = .703$.

Table 46. Linear Mixed Model Predicting Heart Rate Variability from Trial, Loneliness, and Covariates (Trial 3 vs Trial 4)

Predictor	Estimate (B)	SE	df	*t*	95% CI (Lower, Upper)	*p*
Intercept	76.47	21.65	52.19	3.53	[33.06, 119.88]	**.001****
Trial 3 vs Trial 4	–8.91	11.39	49.90	–0.78	[–31.78, 13.96]	.438
Loneliness	–0.59	0.26	71.33	–2.28	[–1.11, –0.08]	**.025***
Depression	–0.21	0.60	47.17	–0.36	[–1.42, 0.99]	.722
Social Anxiety	1.19	0.45	46.10	2.64	[0.28, 2.10]	**.011***
Trust	–4.83	4.41	45.33	–1.10	[–13.72, 4.06]	.279
Behavioural Social Avoidance	0.28	0.40	46.85	0.71	[–0.53, 1.09]	.480
Trial × Loneliness	0.10	0.25	49.90	0.38	[–0.41, 0.61]	.703

Note. Trial was dummy-coded (Trial 3 = reference, social engagement). The "Trial 3 vs Trial 4" coefficient reflects the difference in HRV between the social observation and social engagement conditions.

As shown in Figure 81, higher loneliness was associated with lower HRV across both social observation and social engagement contexts. The absence of a significant trial × loneliness interaction indicates that the negative association between loneliness and HRV did not differ between trials, suggesting a consistent relationship across social observation and engagement conditions. Although HRV tended to decrease with increasing loneliness in both trials, the magnitude of this association was comparable across contexts.

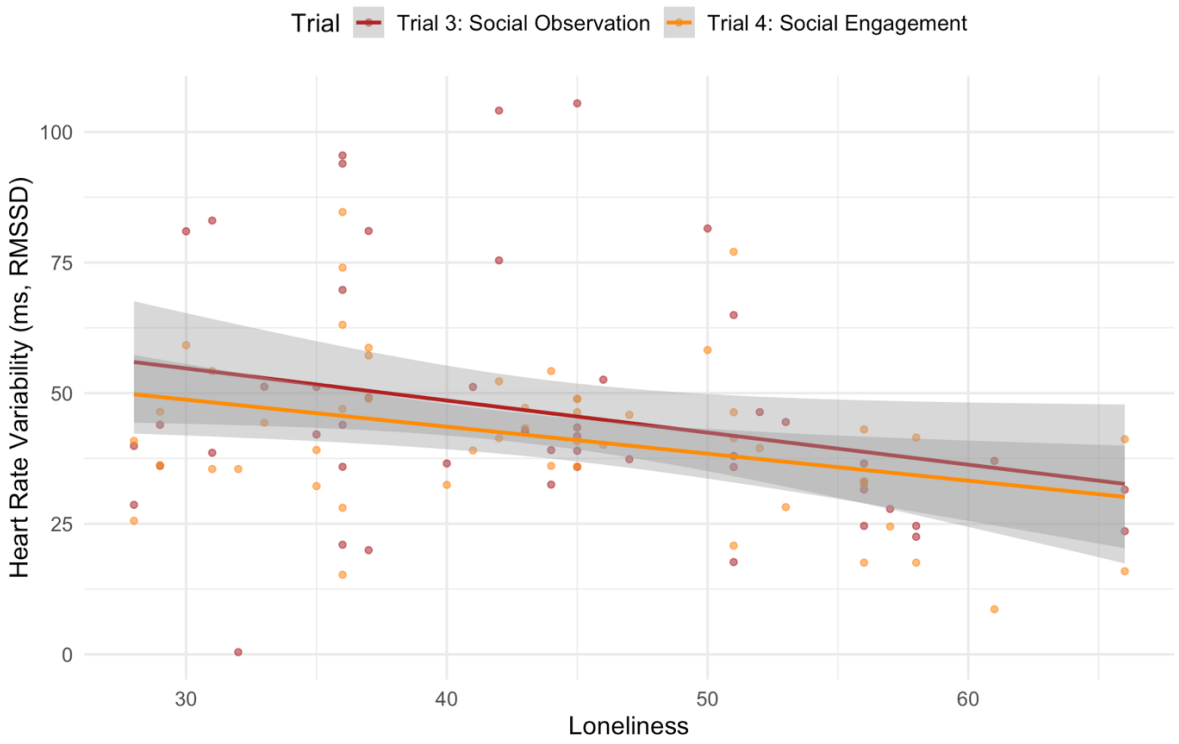


Figure 81. Interaction Between Loneliness and Trial on Heart Rate Variability (HRV)

Note. The scatterplot shows the relationship between loneliness and HRV (RMSSD, ms) across two VR trials: Trial 3 (solid red line) and Trial 4 (solid orange line). Shaded areas represent 95% confidence intervals. HRV decreased with increasing loneliness in both trials, with similar slopes across conditions.

3.5.2. Loneliness and Interpersonal Distance: Social Observation vs Social Engagement

An LMM was conducted to examine whether loneliness, trial condition (Trial 3 vs. Trial 4), and their interaction predicted interpersonal distance (IPD), while controlling for depression, social anxiety, trust, and behavioural social avoidance. The model included a random intercept for participant to account for repeated measures across trials. The overall model explained 28.6% of the variance through fixed effects (marginal R^2 = .29) and 56.2% when including random effects (conditional R^2 = .56). The results revealed a significant main effect of trial, B = –0.44, SE = 0.07, t (48.90) = –6.11, p < .001, indicating that participants maintained significantly less interpersonal distance in Trial 4 compared to Trial 3 (Table 47).

Loneliness was also a significant predictor, $B = 0.019$, $SE = 0.0065$, t (80.79) = 2.93, $p = .004$, suggesting that higher loneliness was associated with greater interpersonal distance. Importantly, a significant interaction between trial and loneliness emerged, $B = -0.018$, $SE = 0.0071$, t (48.90) = −2.48, $p = .017$, indicating that the relationship between loneliness and IPD was stronger in Trial 3 than in Trial 4 (Figure 82). Among covariates, trust significantly predicted IPD, $B = -0.23$, $SE = 0.11$, t (43.70) = −2.17, $p = .035$, such that lower trust was associated with greater distance. Depression, social anxiety, and behavioural social avoidance were not significant predictors. These findings suggest that loneliness and trust contribute to interpersonal spacing behaviour in immersive virtual social environments and that this effect varies depending on the type of social task.

Table 47. Linear Mixed Model Predicting Interpersonal Distance from Trial, Loneliness, and Covariates (Trial 3 vs Trial 4)

Predictor	Estimate (B)	SE	df	t	95% CI (LL, UL)	p
Intercept	1.94	0.48	45.08	4.06	[0.98, 2.89]	**.0002***
Trial 3 vs 4	−0.44	0.07	48.90	−6.11	[−0.58, −0.30]	**< .001***
Loneliness	0.019	0.0065	80.79	2.93	[0.0063, 0.0318]	**.004***
Depression	−0.0099	0.015	45.07	−0.68	[−0.0384, 0.0187]	.502
Social Anxiety	0.017	0.011	45.23	1.54	[−0.0045, 0.0382]	.130
Trust	−0.23	0.11	43.70	−2.17	[−0.44, −0.023]	**.035***
Behavioural Social Avoidance	−0.0024	0.0096	46.26	−0.25	[−0.0213, 0.0165]	.805
Trial × Loneliness	−0.018	0.0071	48.90	−2.48	[−0.0317, −0.0037]	**.017***

Note. IPD was based on the closest approach within 3 meters of the virtual agents. Trial was dummy-coded (Trial 3 = reference). Loneliness predicted greater IPD, and trust predicted lower IPD. The Trial × Loneliness interaction was significant.

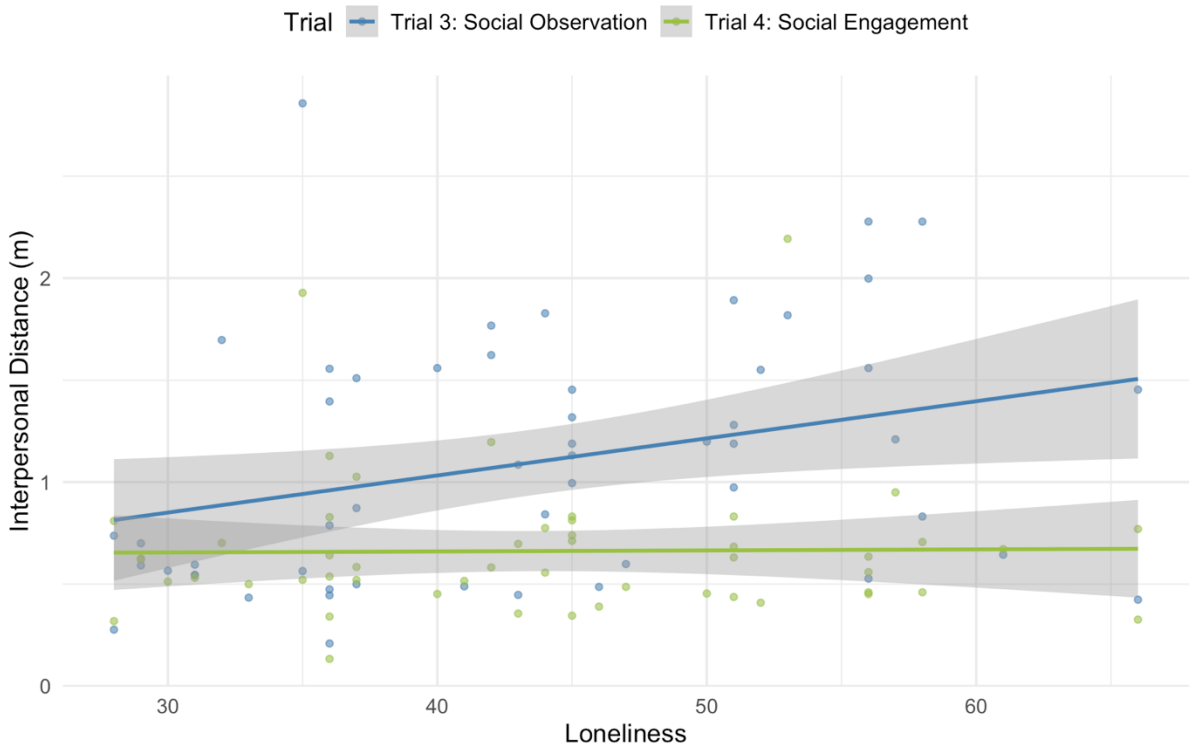


Figure 82. Interaction Between Loneliness and Trial on Interpersonal Distance

Note. The scatterplot illustrates interpersonal distance (in meters) as a function of loneliness in Trial 3 (solid purple line) and Trial 4 (solid pink line). The shaded areas represent 95% confidence intervals. A significant interaction suggests that loneliness was more strongly associated with increased distance during social observation (Trial 3) than during social engagement (Trial 4).

4. Discussion

This study examined loneliness through physiological regulation (heart rate variability) and embodied behavioural avoidance (interpersonal distance) across different non-social and social contexts within immersive virtual reality. The findings offer novel insights to the loneliness literature by integrating objective measures of autonomic regulation and spatial metrics.

At the level of social preference, higher loneliness was significantly associated with a greater likelihood of choosing alone virtual agent rather than those in a group. This result extends previous self-report findings suggesting that lonely individuals may avoid social settings (Gable, 2006). This pattern might suggest that loneliness may bias early

avoidance evaluations, consistent with cognitive theories indicating heightened sensitivity to potential social threat cues.

In terms of physiological regulation, during non-social observation in Trial 1, loneliness showed only a marginal negative association with HRV, suggesting that, in the absence of social cues, loneliness is not robustly linked to autonomic regulation. Moreover, during social observation in Trial 3, loneliness again showed a marginal *negative* association with HRV. It might suggest that lonely individuals' autonomic nervous system is less flexible during observation. Meanwhile, interestingly, social anxiety showed a marginal *positive* association. However, these effects did not reach conventional significance thresholds, and they were trend-level patterns rather than significant effects. The absence of a significant models might indicate that passive exposure to agents is not sufficient to evoke strong autonomic differences linked to loneliness. Meanwhile, the marginal positive association between social anxiety and HRV might reflect increased regulatory during social presence. However, during active social engagement, the pattern in loneliness changed substantially. In line with the Neurovisceral Integration Model (NIM; Williams et al., 2015), loneliness was *negatively* associated with HRV, even though social anxiety was controlled in thee analysis. It might indicate that, when individuals are required to engage socially, higher loneliness is associated with diminished parasympathetic regulation. This is consistent with previous findings linking loneliness with reduced autonomic flexibility (Smith & Pollak, 2022) which supports the hypothesis that lonely individuals may experience elevated physiological stress even in non-threatening environments. This is aligned with the view that loneliness is especially salient in interactive social contexts (Cacioppo et al., 2017). These findings can be also interpreted in the light of Social Safety Theory (SFT) which

was elaborated in Chapter 1. According to SFT (Slavich, 2020), the brain continuously scans for social threats and reduced HRV might explain the physiological cost of perceived social danger, where the body prioritises short-term survival over long-term affiliative functioning. In a way, combined with the insights from evolutionary aspect of loneliness, it can be assumed that lonely individuals are not just emotionally and mentally disconnected, but they are also biologically primed to perceive the social world as unsafe. Moreover, social anxiety was again *positively* associated with higher HRV during social observation engagement, suggesting a different regulatory profile from loneliness. This finding may reflect a compensation mechanism where individuals with social anxiety engage in greater self-regulation to manage the discomfort (Kemp et al., 2012).

In terms of interpersonal distance, during social observation in Trial 3, IPD demonstrated a clear and statistically robust association with loneliness. Higher loneliness was significantly associated with greater IPD, even after controlling for depression, social anxiety, trust and behavioural social avoidance. These results might indicate that spatial behaviour is a particularly sensitive behavioural marker of loneliness. Within the framework of Hall's Proxemic Theory and the Evolutionary Model of Loneliness (Cacioppo & Hawkley, 2009), greater IPD can be understood as a self-protective spatial strategy. This can be also understood as a behavioural safety mechanism explained in Social Safety Theory. SFT suggests that maintaining greater distance is a self-protective response, which aims to reduce risk especially when social cues are ambiguous or unpredictable. Hence, greater IPD might reflect a strategic avoidance which was developed as an adaptive system, however, becomes maladaptive response in social interactions. Moreover, these findings can be also understood in

terms of Attachment Theory. As explained in Chapter 1, loneliness is highly correlated with avoidant attachment, in which individuals typically prefer physical and emotional distancing (Kaitz et al., 2004). Perhaps, these trait-level tendencies mirrored the behavioural patterns among lonely individuals observed in this study. In contrast, this effect was reduced during social engagement (Trial 4), and loneliness was not significantly associated with IPD. Instead, trust emerged as the only significant factor, with lower trust was associated with greater IPD. There could be several explanations for this. First, the difference might be task-dependent where passive observation elicited more avoidance tendencies than active interaction. Second, the difference might be due to habituation effect, where repeated exposure to same virtual environment across trials led to familiarity, hence reduced threat sensitivity. Third, when social interaction is required, trust-related appraisals override loneliness-related avoidance. This finding supports previous work on distrust in loneliness (Lieberz et al., 2021) suggesting that trust may serve as a buffer against social avoidance.

To put in a nutshell, when social choice is ambiguous, lonely individuals preferentially select alone agents; when proximity is optional, they maintain greater interpersonal distance; when social observation is required, behavioural avoidance is reduced while physiology dysregulates; and when social engagement is demanded, interpersonal trust, rather than loneliness, emerges as the primary determinant of behavioural avoidance.

Overall, this study provides novel insights into loneliness research by combining immersive virtual reality with objective behavioural (interpersonal distance) and physiological (heart rate variability) measure to move beyond self-report studies. Moreover, the distinction between social observation and engagement, and modelling

loneliness alongside depression, social anxiety, avoidance and trust, demonstrate that loneliness has context-dependent effects on social preferences, behavioural avoidance and autonomic regulation. As of now, this is the first experimental study jointly assessing embodied avoidance and physiological regulation in loneliness within VR. Collectively, the findings advance the theoretical understanding of loneliness, addressing key methodological gaps in the literature, and offer implications for interventions.

The current study has some limitations to acknowledge, and the findings should be interpreted carefully. First, the study relied on a modest sample size (N=53), limiting statistical power for detecting smaller effects. Future research should replicate these findings in larger and more diverse samples. Second, the VR trials were brief and did not include interactions with the virtual agents, therefore, may not fully reflect real-world social dynamics. Third, the virtual agent was constrained by having only a female virtual agent for Trial 2, which may have introduced bias in social perceptions and behaviours. Lastly, HRV was the sole physiological index; incorporating additional markers (e.g., skin conductance, cortisol) could provide a more comprehensive understanding of stress responses.

5. Conclusion

The current study advances our knowledge of loneliness in terms of both physiological and behavioural markers in virtual environment. The findings underscore the dynamic interplay between loneliness, trust and social context, indicating that avoidance in loneliness is not constant but rather changes depending on the social demands. From a clinical psychology perspective, these results provide a reference point

for the potential of VR as a tool for assessment and intervention for avoidance behaviours of lonely individuals. For instance, VR interventions could help lonely individuals to gradually lessen their both cognitive and behavioural avoidance strategies in a controlled exposure to social scenarios. Furthermore, fostering interpersonal trust might be a key therapeutic target in reducing behavioural avoidance tendencies. Ultimately, this study bridges a critical gap in loneliness literature and provides a more nuanced understanding of how loneliness shapes social interactions and preferences by combining behavioural physiological and contextual elements.

CHAPTER 7

General Discussion and Concluding Remarks

Loneliness is not an absence, but an echo of unheard voices. In its silence, there is a quiet longing for connection, waiting to be heard, to be seen, to be understood and to matter…

1. General Discussion

1.1. Summary and Integration to Findings

Loneliness is increasingly recognised as a significant global public health issue. It is an inevitable component of existence and can occur at any age (Cacioppo & Hawkley, 2009). While episodes of loneliness are considered normal and essential for survival because they ensure that we strengthen our social connections and protect ourselves from the dangers of living on the social perimeter, chronic loneliness has detrimental consequences on physical and mental health (Cacioppo et al., 2015; Bangee & Qualter, 2018). Cacioppo et al. (2006) proposed that the awareness of loneliness evolved to act as a signal that one's connections to others are frayed or broken and to motivate the maintenance of connections, which are necessary for our health and well-being as well as the survival of our genes. That means in a paradoxical way, loneliness promotes both the explicit desire to connect with others but also the implicit hypervigilance for social dangers (Cacioppo & Hawkley, 2009; Cacioppo et al., 2014). Specifically, studies show that loneliness promotes a cognitive bias towards perceiving social threats, through attention, interpretation, and memory biases (Cacioppo et al., 2014). While there are many outstanding questions in the literature as highlighted by recent studies, loneliness remains as an understudied topic. There are still many important aspects and layers of loneliness which need to be explored.

Therefore, the current thesis set out to investigate loneliness through a multifaceted lens, integrating theoretical and experimental approaches. Across six chapters, I examined loneliness from multidisciplinary theoretical framework, spanning from literature synthesis for computerised experimental studies to immersive virtual

reality experiments. This comprehensive approach not only unpacked the predictors of loneliness but also provided methodological innovation through VR-based paradigms.

Chapter 1, *Multidisciplinary Introduction to Loneliness*, provided a multidisciplinary theoretical foundation to understand loneliness as a multifaceted, complex and biopsychosocial phenomenon shaped by evolutionary, neural, cognitive, psychological and social factors. This chapter introduced the taxonomy of loneliness distinguishing emotional, social, collective and existential loneliness and clarified key distinctions from related concepts, such as social isolation, aloneness and solitude (Motta, 2021; Russell, 1996; Weiss, 1975; Dunbar, 2014, Hall, 1996). Importantly, the chapter highlighted the distinction between situational and chronic loneliness. This chapter further informed about theoretical frameworks. Evolutionary Theory positioned loneliness as an adaptive signal for social reconnection that becomes maladaptive in modern contexts through hypervigilance to social threats (Cacioppo & Hawkley, 2009), while neuroscientific evidence implicated amygdala hyperactivity, reduced activation in prefrontal cortex, altered activity in insula, and reduced response in ventral striatum in lonely individuals (Morr et al., 2022a; Vitale & Smith, 2022; Lam et al., 2021). Cognitive-behavioural models emphasised self-reinforcing biases that perpetuate isolation in a cyclical interplay (Käll et al., 2020; Peplau & Perlman, 1982; Cacioppo & Hawkley, 2009). Social theories further revealed the importance of proximity, shared attitudes and mutual ties, while also highlighting how perceiving threats activates behavioural self-protection which leads to withdrawal and avoidance (Slavich, 2020; Weiss, 1975; Cacioppo et al., 2009). Chapter 1 also reviewed risk factors: biological, psychological, sociocultural and technological (Morr et al, 2022b; Bowirrat et al., 2023; Cacioppo et al., 2015; Sparks et al., 2024; Abdellaoui et al., 2019a; Buecker et al.,

2020; Shovestul et al., 2020; Miguel et al., 2024). Moreover, this chapter highlighted the growing global concerns in terms of detrimental consequences to overall health (Leigh-Hunt et al., 2017; Quadt et al., 2020) and increasing prevalence of loneliness which requires a need for increased public awareness (Barreto et al., 2022). Overall, this comprehensive synthesis produced a novel integrative framework and directly informed the thesis's experimental investigations on predictors, cognitive biases, and physiological reactivity in loneliness, and the use of VR to simulate real-world social encounters in the subsequent chapters.

Chapter 2, *Study 1: Scoping Review of Experimental Studies on Cognitive Biases in Loneliness*, systematically mapped the experimental evidence on cognitive biases in loneliness within the "Social Information Processing" framework (Crick, 1995) and extended the "Evolutionary Theory of Loneliness" (Cacioppo & Hawkley, 2009) by adding "*approach-avoidance bias*" along with attention and interpretation biases. While findings from studies on the approach-avoidance bias revealed meaningful distinctions of the dual nature of loneliness based on its chronicity (Saporta et al., 2021; Smith & Pollak, 2022), findings from studies in attention and interpretation biases yielded mixed results (e.g., Qualter et al., 2013; Lodder et al, 2016). However, brain imaging studies appeared to be the most reliable measure to detect attention bias (e.g., Cacioppo et al., 2009; Kanai et al., 2012), and the interpretation bias is more consistently expressed by lonely adults in behavioural studies (e.g., Grocott et al., 2024; Nombro et al., 2022). Overall, this review emphasised the need for inclusion of children and adolescents' sample to compare changes across development; integration of behavioural, neural, and physiological data; research investigating approach-avoidance bias to fill the

methodological, empirical, and evidence gaps; and ecologically valid paradigms simulating real-world social experiences, such as VR paradigms.

Chapter 3, *Study 2: Multivariate Modelling of Loneliness*, presented three empirical studies using multivariate modelling to investigate predictors of loneliness. ***Study 2A*** explored sociodemographic predictors of loneliness in adult sample. The findings supported previous studies and revealed that young adults, individuals who are single and separated, those who live alone or in shared house, housemakers and unemployed, had the higher level of loneliness (Branje et al., 2021; Barreto et al., 2021). Age and living condition were the strongest predictors, suggesting that the experience of loneliness particularly peaks during developmental transitions and when lacking daily social connections. These findings align with the structural theories of loneliness, underscoring how social contexts shape vulnerability to loneliness. For instance, as explained in Chapter 1, according to "Social Network Theory" (Moreno, 1937), loneliness is lack of integration into social networks, such as being isolated in terms of proximity. ***Study 2b***, aimed to address the gap in the literature by investigating the psychological predictors of loneliness, more specifically the dynamic interplay between loneliness, depression, social anxiety and alexithymia with both mediating and moderating pathways. The findings revealed that alexithymia influences loneliness both directly and indirectly via depression and social anxiety, with depression having the strongest mediating effect and social anxiety amplifying the depression and loneliness link. These findings underscored the importance of emotional processing difficulties as a central driver of loneliness and supported previous research (Zhang et al., 2023; Qualter et al., 2009). Furthermore, ***Study 2c*** examined the behavioural and social predictors of

loneliness focusing on depression, avoidance and trust, and provided novel insights while supporting prior findings (Yuan et al., 2022; Kraav et al., 2021; Wong et al., 2022; Inagaki et al., 2016). Based on findings, depression had the strongest effect on loneliness, but behavioural social avoidance significantly mediated this effect. Notably, trust moderated the relationship between overall avoidance and loneliness, suggesting that even high avoidance does not necessary lead to loneliness if interpersonal trust is present. On the other hand, cognitive avoidance alone was not a direct predictor but influenced loneliness indirectly via its impact on behavioural avoidance. This multi-layered model revealed an important sequential pathway: depression → cognitive avoidance → behavioural avoidance → chronic loneliness.

Chapter 4, *Study 3: Attention and Interpretation Bias in Facial Emotion Processing***,** with the knowledge from Chapter 2, I addressed the empirical gaps and designed an advanced online experimental studies to explore attention and interpretation biases in facial emotion processing, focusing on how individuals with high versus low loneliness process emotional facial emotions across ages (adolescent, young, middle age, and older adults). First, I conducted a pilot study for in-depth investigation into the temporal dynamics of emotion perception and the interpretation of ambiguous facial expressions to provide a more robust investigation for the main experiments. With the insights gained from this pilot study, two experiments were employed with age-specific facial emotion processing tasks; video clips of faces with neutral expressions that gradually morphed into full emotional expressions to measure attentional sensitivity and decoding accuracy; and static images with neutral faces and different emotional intensity: 25%, 50% and 75% to measure misinterpretation and decoding accuracy of

neutral and ambiguous faces. These two experiments revealed that loneliness is influenced by both emotion type and age in facial emotion processing. Age-specific patterns in facial emotion processing, where high-lonely adolescents showed decreased attentional sensitivity to positive emotions and increased interpretation bias for neutral and ambiguous facial emotions, while older adults demonstrated a positive cognitive bias with reduced accuracy for negative emotions. Overall, this chapter provided partial support for cognitive models of loneliness (Cacioppo et al., 2014; Bangee & Qualter, 2018; Lodder et al., 2015) and highlighted the importance of examining age-specific cognitive biases.

Chapter 5, *Study 4: Approach-Avoidance Bias Towards Emotional Cues in Loneliness***,** I aimed to explore how loneliness modulates embodied approach–avoidance responses, to emotional cues in VR. Using a novel immersive "*Affective Approach-Avoidance VR Paradigm*", this chapter included two experiments: the first carried out at Radboud University in Netherlands and the second at University of East Anglia in UK. Across both experiments, approach-related amplitude responses did not significantly differ by emotion or loneliness, however, lonely adults demonstrated embodied avoidance for ambiguous and negative facial stimuli. In terms of velocity of embodied responses, neither approach nor avoidance were robustly modulated by loneliness or emotion. Overall, the findings highlight a crucial point suggesting that loneliness is embodied, not just cognitive. Lonely individuals do not only have cognitive biases towards negative emotional cues (Cacioppo et al., 2014; Cheeta et al., 2021), but they also behaviourally avoid them. This supports the theoretical studies, particularly "*The model of approach-avoidance interpersonal motivation*" by Gable and Gosnell (2013) in which approach and

avoidance motivations were suggested to operate simultaneously. In conclusion, these two experiments offered ecologically valid insights into the embodied behavioural responses in loneliness and demonstrated the value of VR in capturing subtle real-time avoidance behaviours.

Chapter 6, *Study 5: Loneliness and Avoidance: Physiological and Behavioural Responses*, I explored the relationship between loneliness and physiological and behavioural avoidance in a novel "*Virtual Reality Social Interaction Paradigm*". The findings complemented previous experiments in avoidance in Chapter 5 by integrating autonomic regulation (HRV) and interpersonal distance (IPD) measurements across different social contexts. The findings revealed novel insights into the behavioural avoidance in loneliness. First of all, loneliness was associated with the social preference with lonely individuals choosing the alone virtual agent rather than those in a group, indicating social avoidance. Furthermore, loneliness was also negatively associated with HRV, suggesting reduced parasympathetic regulation and elevated physiological stress, even in non-social environments. Loneliness was also associated with greater IPD in social contexts, indicating that lonely individuals might be using self-protective behaviours. Importantly, trust again played a significant moderating role, with higher trust was associated higher HRV and smaller IPD, suggesting that greater interpersonal trust is associated with enhanced physiological regulation and reduced behavioural avoidance in lonely individuals in social contexts. Overall, this study bridged a critical gap in loneliness literature and provided a more nuanced understanding of how loneliness shapes social interactions and preferences by combining behavioural, physiological and contextual elements.

1.2. Theoretical, Methodological and Clinical Implications

1.2.1. The Refinement of Evolutionary Theory: Integrating Cognitive Biases and Approach-Avoidance Mechanism

This thesis first provided empirical support for the "Evolutionary Theory of Loneliness" by Cacioppo and Hawkley (2009), which posits a loneliness paradox: a strong desire for reconnection with simultaneous hypervigilance to negative social and emotional cues. Integration of Social Information Processing (SIP) model (Crick & Dodge, 1994) further helped us to understand this paradox by providing new insights into how lonely individuals process emotional and social information at multiple stages, in attention and decoding, interpretation and behavioural response. This framework helped bridging the cognitive theories with behavioural frameworks, informing us about the embodied responses. Building on this foundation, the thesis refined the evolutionary model by incorporating *Approach–Avoidance Bias* (AAB) as a behavioural and physiological mechanism reinforcing the loneliness paradox. While approach-avoidance motivations have been studied in loneliness, the present thesis made a key theoretical contribution by embedding AAB within the cognitive bias framework of the loneliness loop. Drawing on the SIP model, the VR experiments extended this framework, revealing embodied avoidance responses: lonely participants displayed stronger avoidance bias towards ambiguous and negative faces, maintained greater interpersonal distance (IPD), and had reduced heart rate variability (HRV) in social contexts. These patterns indicate that cognitive biases manifest in measurable behavioural withdrawal and physiological dysregulation in ecologically valid settings. This challenges purely "top-down" cognitive models by highlighting the role of bottom-

up physiological dysregulation (e.g., reduced HRV as a marker of autonomic inflexibility) and demonstrating that behavioural and physiological pathways are equally central to the maintenance of loneliness. The proposed extension positions AAB as a bridge between cognitive distortions and social behaviours, offering a mechanistic link that unites evolutionary, cognitive, and behavioural approaches.

Anchored in "Evolutionary Theory of Loneliness" (Cacioppo & Hawkley, 2009), the findings supported the idea that loneliness is adaptive as an alarm system evolved to motivate for reconnection, however, it becomes maladaptive when prolonged. We developed the "*Cascade Model of Loneliness*" in this thesis to extend the current framework synthesising insights from multiple disciplines and findings from our studies to create a comprehensive representation of how loneliness emerges, escalates and becomes chronic through interconnected psychological, cognitive, behavioural and physiological processes.

The Cascade Model of Loneliness (Figure 83) illustrates how various biological, psychological and social factors might interact overtime to lead situational loneliness to chronic loneliness through self-reinforcing feedback loop. At the first stage of this cascade model, *Predisposing Vulnerabilities*, we outlined three underlying factors making an individual more susceptible to experience loneliness: (a) Biological (e.g., genetic, neurobiological); (b) Psychological (e.g., attachment styles, mental health problems, personality traits); (c) Sociocultural (e.g., demographics, urbanisation, migration, technological). These vulnerabilities might trigger subjective experience of feeling disconnected, regardless of social network size, which can be situational, especially when life circumstances reduce social contact or connection (e.g., retirement, migration, divorce). This *Perceived Social Isolation* involves a mismatch between desired

and actual connections creating a motivational conflict: a desire to reconnect (approach) vs fear of rejection and hypervigilance to social threats (avoidance). This consequently activates *Cognitive Biases*; (a) Attention bias, hyper focusing on negative emotional and social cues; (b) Interpretation bias, tendency to misinterpret neutral and ambiguous emotional and social cues; (c) Approach-Avoidance bias, withdrawal from social engagement. These biases essentially reduce opportunities for reconnection. At this stage, we suggest that cognitive biases might lead to cognitive avoidance first, however, if the absence of interpersonal trust, cognitive avoidance might turn into *Behavioural Avoidance*, such as withdrawing from social interactions to self-protect from perceived threats. If behavioural avoidance is persistent (e.g., social withdrawal and greater interpersonal distance), it might reinforce isolation and contribute the transitioning to *Chronic Loneliness* which may feedback to worsen cognitive biases and vulnerabilities. At this stage a self-reinforcing cycle might develop due to cognitive biases, increased sensitivity to social threats, reduced ability to synchronise with others.

To put in a nutshell, each stage may reinforce the next, potentially creating a vicious cycle. Consequently, chronic loneliness is rooted, with lasting psychological, social, and physiological consequences. Therefore, this model presents a heuristic process illustrating how loneliness may evolve from initial predisposing vulnerabilities into a self-sustaining condition, emphasizing the interplay between perception, cognition, and behaviour. However, it is important to note that the proposed cascade model requires more empirical support from future studies, and it that does not posit a definitive casual sequence. Even so, interventions targeting specific stages (e.g., cognitive restructuring for biases) could still help disrupting the cascade.

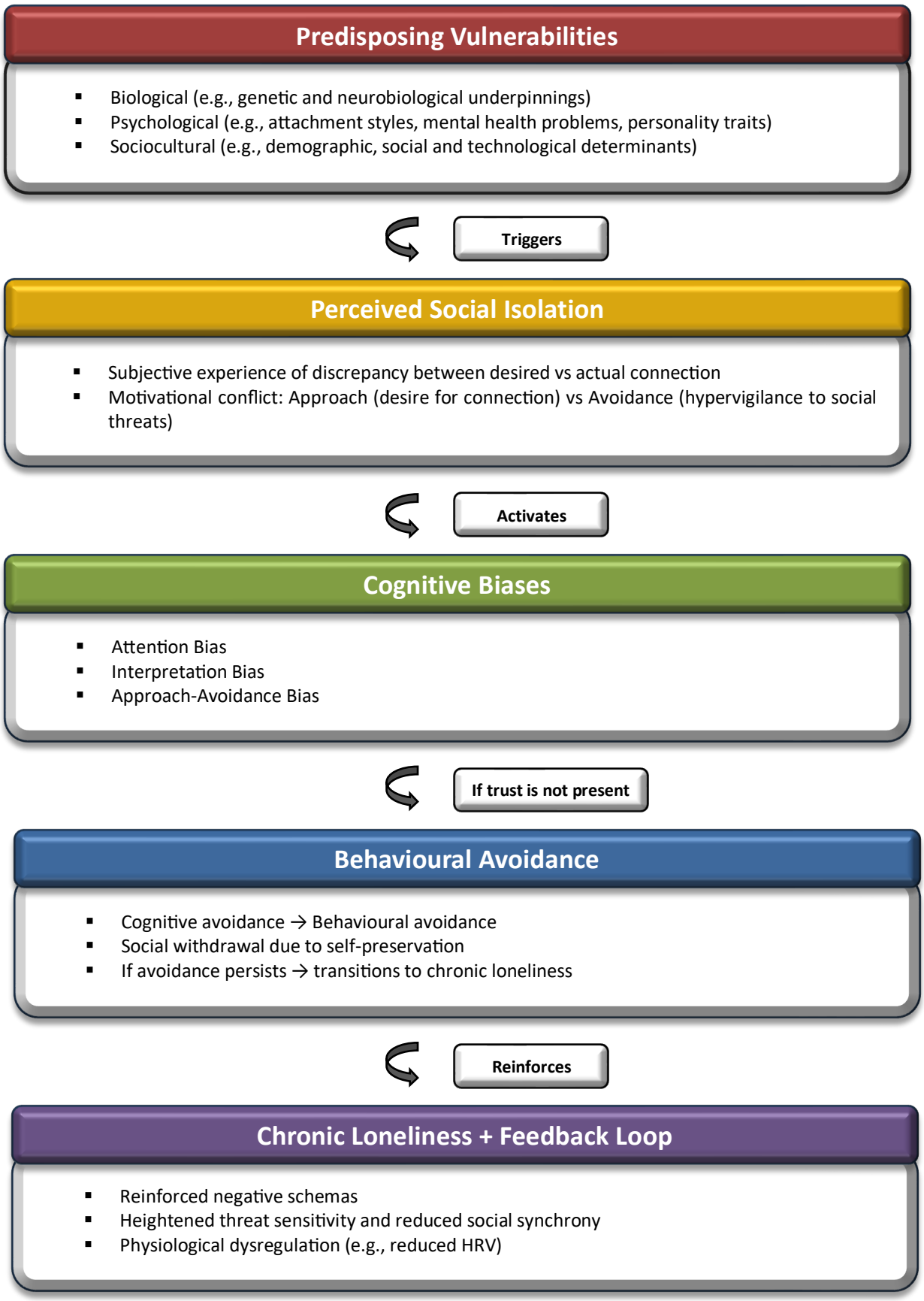


Figure 83. The Cascade Model of Loneliness

1.2.2. A Novel Framework for the Divergent Motivational Mechanisms of Situational and Chronic Loneliness

This thesis also provides a critical understanding of the differences between situational and chronic loneliness while investigating cognitive and behavioural mechanisms. While previous research has largely approached loneliness as a uniform construct, the scoping review revealed a critical understanding of the dual nature of loneliness based on its chronicity. Saporta et al. (2021) reported that chronic loneliness reinforced greater social avoidance (preference for greater interpersonal distance), possibly because of fear of rejection, while situational loneliness increased approach motivation, suggesting that momentary feelings of loneliness can enhance the drive for social connection, unlike chronic loneliness. Therefore, we hypothesis that, situational loneliness might increase approach motivation to reconnect and temporarily heighten social interaction seeking, in contrast, persistent social withdrawal and social avoidance caused by cognitive biases might lead to chronic loneliness which reinforce the self-perpetuating cycle.

1.2.3. Novel Applications of Virtual Reality and Heart Rate Variability in Loneliness Research

As of now, this is the first application of immersive VR technology in loneliness research which marked a significant methodological advancement by introducing ecologically valid, controlled and real-time measurements of behavioural responses. Unlike traditional behavioural tasks using joysticks, VR allowed a unique opportunity for participants to engage in embodied social scenarios that closely simulated real-time dynamics. Moreover, the use of HRV offered a multimodal assessment of loneliness related hypervigilance and avoidance. This approach not only enhanced ecological

validity by mimicking the complexity of real-time social encounters but also addressed the limitations of self-reports, which are prone to biases.

1.2.4. Novel Evidence for Age-Specific Facial Emotion Biases in Loneliness Research

Another crucial key novelty of this present thesis is that this is the first study systematically investigate attention and interpretation biases regarding facial emotion process across different developmental stages in lonely individuals: adolescents, young adults, middle-aged adults and older adults. More importantly, the experiments employed age-matched face stimuli, which is also a first in the literature, ensuring ecological validity and reduced potential confounds. These two novel approach established a new methodological standard in loneliness research and provides the first empirical evidence for age-dependent differences in facial emotion processing in loneliness. These implications are crucial, suggesting that psychological interventions targeting maladaptive thinking and cognitive distortions in loneliness should need to be developmentally tailored to be effective.

1.2.5. Novel Methodological Contributions: Confounding Variables and Key Predictors

Another strength and novel contribution of this PhD thesis is the inclusion of alexithymia as a cofound variable while exploring facial emotion processing in loneliness. Prior research has predominantly controlled for depression and social anxiety; however they lack including alexithymia, which is characterised by difficulties in identifying and describing emotions and frequently comorbid with loneliness (Grynberg et al., 2012; Cook et al., 2013). By incorporating alexithymia, the studies in this thesis advanced methodological quality in loneliness research. Additionally, we aimed

to pioneer the examination of avoidance, both cognitive and behavioural, in relation to loneliness by using validated avoidance scale (Ottenbreit & Dobson, 2004). The inclusion of avoidance provided a novel insights into the maintenance of the experience of loneliness. Last but not least, our findings represent the first empirical evidence of trust as a buffer moderating the relationship between avoidance and loneliness. This crucial understanding underscores its protective mechanism of interpersonal trust in interpersonal relationships, and position trust as a cornerstone of adaptive social functioning. These methodological contributions extend the conceptual and empirical boundaries of loneliness research and advances previous studies.

1.2.6. Clinical Implications for Cognitive Bias Modification and Cognitive Behavioural Therapy

The findings from studies in this PhD thesis offer valuable clinical implications for refining Cognitive Bias Modification (CBM) and Cognitive Behaviour Therapy (CBT) interventions tailored specifically to loneliness. First of all, the age-specific pattern in attention and interpretation biases emphasise the need for developmentally tailored CBM protocols. For instance, CBM for adolescents could focus on enhancing recognition of positive emotional cues and reducing threat vigilance to ambiguous and neutral facial emotions. This could potentially disrupt the self-reinforcing cycle of loneliness and promote more adaptive social engagement. Moreover, the present thesis uncovered a critical bidirectional interplay between loneliness, depression, social anxiety and alexithymia, which is mediated by cognitive and behavioural avoidance and buffered by trust. More specifically, while depression, social anxiety and alexithymia amplify the cognitive biases by increasing the vulnerability to cognitive biases through heightened attention to social threat, negative interpretation of ambiguous cues, which

in turn, exacerbate both emotional distress and ultimately lead to avoidance. Within this framework, trust emerged as a critical buffer, disrupting this cycle by possibly reducing threat appraisals and facilitating interpersonal reconnection. Therefore, CBT could (a) *target emotion regulation skills*, particularly for individuals with alexithymia; (b) *employ behavioural activation* tailored to individuals who have high social anxiety, specifically exposure therapy through VR Cue Exposure Therapy or in vivo exercises; (c) *enhance cognitive restructuring* by challenging maladaptive beliefs that contribute avoidance; (d) *develop trust-building exercises* through simulating positive social interactions to recalibrate expectations and beliefs around intentions of others.

Overall, the complex, multifaceted and bidirectional relationships revealed in this PhD thesis underscore the importance of multicomponent psychological interventions that address cognitive biases, social and behavioural avoidance and lack or low interpersonal trust in lonely individuals. By integrating these factors, interventions could more effectively disrupt the self-reinforcing cycle of loneliness and unlock the loneliness cascade at multiple stages. Notably, a recent comprehensive review of 280 studies reported that psychological interventions, focusing on cognitive biases and behavioural avoidance, generally demonstrated a moderate effect, with some evidence suggesting a large effect on loneliness across the lifespan (Lasgaard et al., 2025). Crucially, they also found that psychological interventions focusing outperform social or network-based approaches, reinforcing the relevance of CBT and CBM mechanisms highlighted in this thesis. Future research should explore how these interventions perform in longitudinal and real-world settings to further refine their efficacy.

1.3. Limitations and Future Directions

Some limitations should be considered when interpreting findings from this thesis and many gaps still need to be addressed.

First, in this thesis, we assessed loneliness employing widely used reliable and validated the UCLA Loneliness Scale which is constructed to measure general or trait loneliness and does not differentiate between situational (transient) and chronic (prolonged) loneliness. In fact, this is a fundamental limitation shared by nearly all existing loneliness scales. Currently, there is no adopted, psychometrically validated and reliable scale measuring situational loneliness except COVID-19-specific questionnaires, such as Loneliness and Isolation during Social Distancing (LISD; Gründahl et al., 2022). LISD was developed specifically for the COVID-19 pandemic context and hence it has limited applicability to general populations. This conceptual and methodological gap is particularly problematic given that there is an emerging evidence suggesting these subtypes may involve distinct cognitive and behavioural mechanisms (Saporta et al., 2021). Consequently, the findings in this thesis must be interpreted as reflecting chronic loneliness rather than situational loneliness. Future research would benefit from developing and validating a questionnaire that can exclusively measure these distinct experience of loneliness with adapted temporal parameters.

Second, the use of UCLA Loneliness scale could be considered as another limitation too, as this scale may capture multiple dimensions of loneliness (e.g., emotional and social) rather than solely social loneliness (Russell, 1996; Cacioppo et al., 2006). The UCLA scale is widely used but there is still a debate over whether they assess loneliness

as a single feeling or multiple types. While most factor analyses suggest that the scale might reflect distinct subtypes (DiTommaso et al., 2004; Salo et al., 2020); others argue that this is just due to how questions are worded (positive vs. negative phrasing; Auné et al., 2022; Penning et al., 2014). Hence, there is still an unresolved debate due to lack to enough research which tested whether these subscales measure different dimensions of loneliness in real-world situations. Future research could benefit from measures specifically targeting social loneliness to isolate its role in cognitive biases.

Third, while the cross-sectional studies in this thesis provided a snapshot of loneliness distribution in a specific sample at a particular point in time and offered insights into the relationship between loneliness and cognitive and behavioural processes, longitudinal studies are needed to examine the life span development of loneliness. This is particularly important, because predictors of loneliness and cognitive and behavioural mechanisms may change across the lifespan. Moreover, the cross-sectional design limits the ability to draw causal conclusions about the observed relationships, highlighting the need for longitudinal research to confirm the proposed mechanisms, including mediation effects.

Forth, even though the current VR paradigms used in the experiments offered valuable platform to investigate approach-avoidance behaviours in loneliness, the VR environment and scenarios were originally designed to explore behaviours related to social anxiety at XR lab at Radboud University in Netherlands. While we adapted the scenarios and trials, the VR paradigm's initial focus on social anxiety may not fully capture the nuances social motivations underpinning loneliness. Therefore, a more elaborated VR scenario tailored explicitly to explore loneliness could incorporate ecologically valid dynamic scenarios involving interactions with the virtual agents that

more accurately reflect real-life behaviours. The tailored VR scenarios could allow for a richer investigation of cognitive biases and loneliness-specific mechanisms from those shared with related construct like social anxiety.

Lastly, another limitation of this thesis is that it did not investigate memory bias, which is well-established cognitive bias in loneliness, due to time constraints within the scope of the PhD. Previous research suggests that lonely individuals demonstrate enhanced recall for negative social information, which contributes to sustained perceptions of social threats and increased social avoidance (Igarashi, 2025; Teneva et al., 2020). The investigation of this memory-avoidance interaction might be particularly important in terms of the transition of situational loneliness to chronic loneliness, as maladaptive recall patterns could solidify negative social schemas. Therefore, we recommend future research to employ comprehensive, longitudinal and multimodal investigation of all four cognitive biases: *attention, interpretation, approach-avoidance and memory*, within the same large sample to understand cognitive and behavioural architecture underpinning loneliness.

2. Concluding Remarks

The current PhD thesis aimed to advance the understanding of loneliness by integrating theoretical frameworks, empirical investigations and innovative methodologies. Specifically, it addressed the following key questions and gaps in the previous literature and sought to:

i. Establish comprehensive multidisciplinary foundation by synthesising evolutionary, neuroscientific, cognitive-behavioural and social theories and to

emphasise its risk factors, consequences and prevalence to inform researchers, clinicians and public policies (Chapter 1),

ii. Systematically synthesise the experimental evidence to map cognitive biases in loneliness, particularly *attention, interpretation* and *approach-avoidance biases*, highlighting conceptual, methodological and empirical gaps in the literature and refining the theoretical model (Chapter 2),

iii. Identify the key predictors of loneliness, particularly sociodemographic, psychological, behavioural and social, using multivariate modelling and to build multidimensional explanatory models by clarifying the relative and interactive contributions of these factors (Chapter 3),

iv. Investigate cognitive mechanism of loneliness by investigating attention and interpretation biases in facial emotion processing across age groups to provide lifespan perspective in developmental difference in cognitive biases with advanced experimental tasks and age-matched stimuli (Chapter 4),

v. Explore embodied behavioural mechanisms by testing real-time approach-avoidance biases towards emotional stimuli in a novel immersive virtual reality paradigm, providing ecologically valid insights into behavioural avoidance in loneliness (Chapter 5),

vi. Integrate behavioural and physiological measures to further explore observable avoidance behaviours by combining heart rate variability and interpersonal distance measures in virtual social and non-social contexts (Chapter 6),

vii. Synthesise findings across theoretical, cognitive, behavioural and physiological levels, informing future research to advance conceptual and methodological approaches in loneliness. Moreover, the contribution of the present PhD thesis to the current loneliness literature has been considered and new questions and potential investigations for future research have been raised (Chapter 7).

In essence, this PhD thesis refines and extends Cacioppo and Hawkley's (2009) Evolutionary Theory of Loneliness by embedding approach-avoidance bias within the self-reinforcing cycle with the integration of both top-down cognitive biases and bottom-up physiological stress response. We conceptualised loneliness as a biopsychosocial process and proposed a novel approach: "*The Cascade Model of Loneliness*". This model critically maps a sequential pathway predisposing vulnerabilities → perceived social isolation → cognitive biases → behavioural withdrawal → chronic loneliness and feedback loop, with interpersonal trust acting as a buffering factor at the behavioural stage.

Consequently, by bridging theory, experimentation and real-time applications, such as how novel methodological tools such as VR and HRV can enhance ecological validity, it provides a foundation for more tailored psychological interventions and sets a roadmap for future loneliness research. More specifically, the findings provide a clear framework for developing age-specific psychological interventions, such as cognitive restructuring for biases, behavioural activation and exposure, trust-building exercises and perhaps physiological regulation training.

Ultimately, this PhD research underscores that loneliness is not just a psychological state but a dynamic, self-reinforcing cycle which can be disrupted through targeted and evidence-based strategies to mitigate its adverse consequences. Overall, loneliness requires scientific and public attention in terms of more holistic multifactorial approach to framing this as public health issue.

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Appendix A

Participant Information Sheets, Consent Forms and Debriefings

ADOLESCENT – PARENT INFORMATION (For Studies in Chapter 4)

The Perception of Facial Expressions of Emotions

Thank you for your interest in this study. Before you decide whether you are happy to take part, please read the following information carefully.

What is this research looking at? This study explores how people perceive different facial expressions of emotions. By understanding these perceptions, we hope to understand more about people's responses to facial expressions.

Does my child have to take part? Absolutely not! Participation is completely voluntary. To take part, the participant needs to be between 13 and 17 years old. You can also ask questions about the study before deciding by emailing the principal researcher (Ceyda Kiyak: C.kiyak@uea.ac.uk). If the participant decides they no longer want to take part, they are free to withdraw at any time without giving a reason. Since this is an online study that takes place in an internet browser on your computer, you or your child is able to withdraw from the study simply by closing the internet browser running the study and the study will automatically end.

What will happen if I agree to take part? If your child volunteers, you will need to fill out consent form on the next screen for their participation. This study will last approximately 15 minutes and will take place online. Your child will respond to demographic questionnaire first, then they will be presented with different video clips and images including different facial expressions. They will need to select an option on which facial expression they saw. They will respond the questions only by pressing space key on their keyboard. After this task, they will respond to questionnaires including social interactions they have (such as loneliness and social relationships) and how they feel about them, and negative feelings they might experience such as general mood.

If they are struggling with negative emotions and wellbeing, or you think they may need any support, we encourage you to contact relevant support services for free and confidential help:

NHS talking therapies: https://www.england.nhs.uk/mental-health/adults/nhs-talking-therapies/

SHOUT: https://giveusashout.org/ Text 'SHOUT' to 85258 for 24/7 mental health support

Red Cross: https://www.redcross.org.uk/get-help/get-help-with-loneliness

Mind: https://www.mind.org.uk/

Will it help me if I take part? There will be no direct benefit to the participant from taking part in this research, but it will benefit the programme of research. But you can join prize draw if you prefer and might have a chance to win £10 shopping voucher.

How will you store the information that I give you? All information which you and your child provide during the study will be stored in accordance with the 2018 General Data Protection Regulation and kept strictly confidential. The chief investigator will be the custodian of the anonymous research data. We will not collect or store any identifiable data. All anonymized data and results will be stored indefinitely in order to comply with open practice standards. The electronic data will be stored on the university secure Research Storage Infrastructure, based on IBM enterprise grade Storage Area Network (SAN) hardware housed in secure, environmentally controlled and monitored data centres. Data will be regularly and automatically backed up to tape with on-site and off-site copies.

How will the data be used? Findings and anonymised research results that arise from the data will potentially be presented at conferences and published in peer-reviewed scientific journals. Before that time, we may make the results available as a preprint on bioRxiv (https://www.biorxiv.org) where new scientific results are often first reported. The anonymized data may be made available to the worldwide scientific community by hosting it on a public website (e.g., OSF or GitHub) to promote transparency in science and to facilitate its potential use in future research by other research groups.

What happens if I agree to take part, but change my mind later? The participant has the right to withdraw and ask us to not use their data. However, please note that anonymity may make it very difficult or impossible to withdraw data retrospectively from the study after completing all of an online session.

How do I know that this research is safe for me to take part in? Although every reasonable effort will be taken to prevent breaches of confidentiality and protect the data we collect, confidentiality during actual Internet communication procedures cannot be guaranteed. However, we will take steps to mitigate as much of this risk as possible by only having access to fully anonymized data which is stored on password protected servers at the University of East Anglia. We will not collect or store any data that can identify you (e.g., your email address or IP address).

This research has been approved by an ethics committee on 15 March 2023. All research in the University is looked at by an independent group of people, called a Research Ethics Committee, to protect your safety, rights, wellbeing and dignity. This research was approved by the Psychology Research Ethics Committee at the University of East Anglia.

You are under no obligation to agree to your child taking part in this research. If you do not agree you can withdraw your consent at any time during the research process without giving a reason.

Contact details

If you have a concern about any aspect of this study, please speak to Ceyda Kiyak (C.kiyak@uea.ac.uk) or their supervisor, Dr Sara Bengtsson (S.bengtsson@uea.ac.uk) and we will do our best to answer your query.

If you remain unhappy or wish to make a formal complaint, please contact the Psychology Ethics Committee at the University of East Anglia who will seek to resolve the matter as soon as possible.

Ceyda Kiyak C.kiyak@uea.ac.uk

Dr Sara Bengtsson S.bengtsson@uea.ac.uk

Dr Gareth Edwards Stephen.G.Edwards@uea.ac.uk

School of Psychology Ethics Committee: ethics.psychology@uea.ac.uk

Head of School Professor Neil Cooper: neil.cooper@uea.ac.uk

Adolescent – Parent Consent

Please read the following declarations and check each box if you understand and agree with it:

- My child and I have read and understand the information sheet (parent/guardian). We have had the opportunity to ask questions about the study and have received satisfactory answers to any of these questions.
- My child and I know that their participation is voluntary, and we know that they are free to withdraw from the study at any time during the online experiment.
- My child and I understand this study has been reviewed and received ethics clearance through the University of East Anglia Ethics Committee.
- My child and I understand that this research will be written up and published.
- My child and I understand that the researchers will not collect any data that could directly identify my child.
- My child and I agree for the research data collected in this study to be deposited in open access archives so that it may be used in other research studies.
- My child and I agree for them to take part in this study.

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ADULT PARTICIPANT INFORMATION (For Studies in Chapter 4)

The Perception of Facial Expressions of Emotions

Thank you for your interest in this study. Before you decide whether to take part, please read the following information carefully.

What is this research looking at? This study explores how people perceive different facial expressions of emotions. By understanding these perceptions, we hope to understand more about people's responses to facial expressions.

Why have I been invited to take part? You have been invited because you responded to an advert for this study. To take part, you need to be over 18 years old.

Do I have to take part? No. It is up to you to decide whether you want to take part or not. Please read the information on this page to help you decide. You can also ask questions about the study before deciding by emailing the principal researcher (Ceyda Kiyak: C.Kiyak@uea.ac.uk). If you decide to take part, you are free to withdraw at any time without giving a reason. Since this is an online study that takes place in an internet browser on your computer, if you want to withdraw from the study simply close the internet browser running the study and the study will automatically end. Please note that we are only able to reimburse participants who complete the study.

What will happen if I agree to take part? This study will last approximately 20 minutes and will take place online. You will respond to a questionnaire first, and then you will be presented with different video clips and images including different facial expressions. You will need to select an option on which facial expression you saw. Then you will respond to several questionnaires about social interactions you have (such as loneliness and social relationships) and how you feel about them, and negative feelings you might experience (your general mood) such as anxiety.

If you are struggling with negative emotions and wellbeing, or you think you may need any support, we encourage you to contact relevant support services for free and confidential help.

NHS talking therapies: https://www.england.nhs.uk/mental-health/adults/nhs-talking-therapies/

SHOUT: https://giveusashout.org/ Text 'SHOUT' to 85258 for 24/7 mental health support

Red Cross: https://www.redcross.org.uk/get-help/get-help-with-loneliness

Mind: https://www.mind.org.uk/

Will it help me if I take part? There will be no direct social, mental or emotional benefit to you from taking part in this research.

How will you store the information that I give you? All information which you provide during the study will be stored in accordance with the 2018 General Data Protection Regulation and kept strictly confidential. The chief investigator will be the custodian of the anonymous research data. We will not collect or store any identifiable data. All anonymized data and results will be stored for ten years in order to comply with open practice standards. The electronic data will be stored on the university secure Research Storage Infrastructure, based on IBM enterprise grade Storage Area Network (SAN) hardware housed in secure, environmentally controlled and monitored data centres. Data will be regularly and automatically backed up to tape with on-site and off-site copies.

How will the data be used? Findings and anonymised research results that arise from the data will potentially be presented at conferences and published in peer-reviewed scientific journals. Before that time, we may make the results available as a preprint on bioRxiv (https://www.biorxiv.org) where new scientific results are often first reported. The anonymized data may be made available to the worldwide scientific community by hosting it on a public website (e.g., OSF or GitHub) to promote transparency in science and to facilitate its potential use in future research by other research groups.

What happens if I agree to take part, but change my mind later? You have the right to withdraw and ask us to not use your data. However, please note that anonymity may make it very difficult or impossible to withdraw data retroactively from the study after completing all of the online session.

How do I know that this research is safe for me to take part in? Although every reasonable effort will be taken to prevent breaches of confidentiality and protect the data we collect, confidentiality during actual Internet communication procedures cannot be guaranteed. However, we will take steps to mitigate as much of this risk as possible by only having access to fully anonymized data which is stored on password protected servers at the University of East Anglia. We will not collect or store any data that can identify you (e.g., your email address or IP address).

This research has been approved by an ethics committee on 15 March 2023. All research in the University is looked at by an independent group of people, called a Research Ethics Committee, to protect your safety, rights, wellbeing and dignity. This research

was approved by the Psychology Research Ethics Committee at the University of East Anglia.

Contact details

If you have a concern about any aspect of this study, please speak to Ceyda Kiyak (C.kiyak@uea.ac.uk) or their supervisors, Dr Sara Bengtsson (S.bengtsson@uea.ac.uk), Dr Gareth Edwards (Stephen.G.Edwards@uea.ac.uk) and we will do our best to answer your query. If you remain unhappy or wish to make a formal complaint, please contact the Psychology Ethics Committee at the University of East Anglia who will seek to resolve the matter as soon as possible.

Ceyda Kiyak C.Kiyak@uea.ac.uk

Dr Sara Bengtsson S.Bengtsson@uea.ac.uk

Dr Gareth Edwards Stephen.G.Edwards@uea.ac.uk

School of Psychology Ethics Committee: ethics.psychology@uea.ac.uk

Head of School Professor Neil Cooper: neil.cooper@uea.ac.uk

Adult Participant Consent

Please read the following declarations and check each box if you understand and agree with it:

- o I have read and understand the participant information.
- o I have had opportunity to ask questions about the study, and if I did, I have received satisfactory answers to these questions.
- o I understand I can withdraw from the study at any point before, during, or after the study without penalty.
- o I understand this study has been reviewed and received ethics clearance through the University of East Anglia Ethics Committee.
- o I understand that this research will be written up and published.
- o I understand that the researchers will not collect any data that could directly identify me.
- o I agree for the research data collected in this study to be deposited in open access archives so that it may be used in other research studies. I understand that any data that leave the research group and/or is published will be anonymized.
- o I understand how to raise a concern and make a complaint.
- o I agree to take part in this study.

Debriefing (For Studies in Chapter 4)

Sometimes people will not want us to use their responses because, for example, they feel they didn't pay enough attention to the questions. Should we use your anonymous responses?
Thank you for participating in this study. Your time and efforts are much appreciated.

- Yes, use my data
- No, do not use my data

This study aims to explore how lonely individuals perceive different facial expressions of emotions. According to previous research, lonely individuals are hypervigilant to negative faces, particularly fearful faces. Moreover, the studies suggest that lonely individuals misattribute neutral faces as negative. By understanding these perceptions of lonely individuals, we hope to develop new psychological interventions.

If you think you may need any well-being support, we encourage you to contact a relevant support service for free and confidential help.

NHS talking therapies: https://www.england.nhs.uk/mental-health/adults/nhs-talking-therapies/

SHOUT: https://giveusashout.org/ Text 'SHOUT' to 85258 for 24/7 mental health support

Red Cross: https://www.redcross.org.uk/get-help/get-help-with-loneliness

Mind: https://www.mind.org.uk/

- Researcher: Ceyda Kiyak (C.Kiyak@uea.ac.uk)
- Supervisor: Dr Sara Bengtsson (S.Bengtsson@uea.ac.uk)
- Supervisor: Dr Gareth Edwards (Stephen.G.Edwards@uea.ac.uk)

Do also contact us if you have any worries or concerns about this research.

School of Psychology Ethics Committee: ethics.psychology@uea.ac.uk

Phone 01603 597146

Head of School Professor Neil Cooper: neil.cooper@uea.ac.uk

Phone 01603 592996

Radboud University

PARTICIPANT INFORMATION (For Experiment 1 in Chapter 5)

Social Interactions in VR

You are invited to take part in a research project conducted at the Behavioural Science Institute of Radboud University. Before you decide whether to take part in this study, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully. Email the researchers if there is anything that is not clear or if you would like more information. Take your time to decide whether you wish to take part or not.

What is the purpose of the study?
The purpose of the study is to investigate how people behave in virtual social interactions and in how far individual differences influence these behaviours.

What will I be asked to do?
In the experiment, you will be immersed in a virtual reality scenario comparable to that of an international conference. You are standing in an open booth with your research-poster. The content of the poster is not important, but you will interact with virtual agents, who are participants of the conference. During the task, you will stand on a low platform and have to observe different aspects of the virtual people approaching.

When can I participate?
To be eligible for the study, you need to be 18 years or older. You shouldn't be sensitive to traveling/motion sickness, suffer from frequent dizziness or have problems with keeping your balance. In addition, you should not have a current diagnosis of any psychiatric or neurological disorder, nor should you be in psychological, psychiatric, or neurological treatment. You should not use psychopharmacologic nor neuroleptic medicine.

Risks
Some people respond strongly to moving pictures and get dizzy and/or nauseous. If you are susceptible to travel sickness, or are sensitive to, e.g., films that are recorded with a hand camera or to fast moving scenes in computer games, it is very likely that you will experience the same in a VR environment. In that case you may want to refrain from participation. But even if you are not familiar with these symptoms, you may start feeling nauseated in a VR environment – this is called cyber sickness. Typically, this subsides when the VR gear is removed - so you should immediately inform the research assistant when you feel unwell during the test session. In addition, it is possible that your answers to some of the questionnaires evoke worries about your health. However,

these are no diagnostic tools, and individual scores do not allow any such interpretation. Since scores are calculated after the data collection is finished, but your data is anonymized at the point of your participation, we will not be able to give you any feedback on your scores. Yet, if you should keep worrying, you should contact your family practitioner and see if s/he shares your concerns.

Participation is voluntary
Your participation in this study is voluntary. If you decide to take part and then later change your mind, either before you start the study, during the test session or afterwards, you can withdraw and, if you wish, your data (up to that point) will be destroyed/deleted. You do not have to justify why you quit.

Data processing
Your personal data such as age, education and gender, as well as the questionnaire data and the data recorded during the task, are stored anonymously. Typically, research data is reported based on group means in conference presentations or publications. You will not be identifiable in any way. Your anonymized data will be stored for 10 years, on encrypted servers of Radboud University, to which only the experimenters have access. It has become common, however, that, after completion of a research project (and publication of results), the anonymized data is made accessible for other researchers in order to allow reanalyses of the data or exploration of other research ideas. We will do that as well in order to be as transparent about our results as possible and allow answering of new research questions.

What if something goes wrong?
If you have complaints about any aspect of the study or your participation, feel free to speak to or contact one of the present research assistants or the principal investigator (g.lange@psych.ru.nl). In addition, you can provide us with feedback via: https://www.ru.nl/bsi/forms/research-participant-feedback-form/.

In the unlikely event that you suffer injury, or your property is damaged as a result of taking part in this research, the University has an insurance policy to cover any harm arising as a result of research participation.

Questions?
For further information about this study you can contact the student researchers/research assistants.

Principle Investigator: Dr. Wolf-Gero Lange Email: g.lange@psych.ru.nl

Informed Consent Checklist

- I am at least 18 years old
- I have read and fully understood the study information
- I have had sufficient time to think about my participation or ask questions
- I confirm that I do not have problems keeping my postural balance
- I confirm that I have NO diagnosis of any psychiatric or neurological disorder
- I confirm that I am NOT in psychological, psychiatric or neurological treatment
- I confirm that I do NOT use psychopharmaca or neuroleptica
- I voluntarily consent to participate in this study

Debriefing (For Experiment 1 in Chapter 5)

Dear Madam, Sir, A couple month ago you have participated in our study social interaction in VR, and you had indicated to be informed about the true nature of the research. First of all, we want to thank you again for your participation.

As you may recall, you were immersed in a virtual environment in which you stood on a platform next to a research poster and were approached by different digital agents. You were instructed to remember eye-colour and names of the agents and were asked to fill in a number of different questionnaires assessing some sociodemographic information and diverse aspects of your personality. In addition to that, we also assessed your body movements (e.g., forward and backward leaning) on the platform.

The aim of this experiment was to study subtle behaviours of people with varying degrees of fear of negative evaluation by others (social anxiety). In particular we wanted to know how individuals with different levels of social anxiety behave when their interpersonal space is violated, namely by being approached by virtual agents.

It was expected that with higher degrees of social anxiety, individuals will move more nervously (i.e. show increased body sway) and lean more backward when being approached. In addition, we think that these postural changes would occur at a greater distance between the individual and the virtual agent.

If you have any questions regarding this study, please do not hesitate to contact the principal investigator, Dr. Wolf-Gero Lange: g.lange@psych.ru.nl. In addition, you can provide us with feedback via: https://www.ru.nl/bsi/forms/research-participant-feedback-form/.

We kindly ask you to keep the methodology used in this experiment confidential by not telling fellow students or potential participants about it. It is important for the purposes of our research that future participants should be naïve to our research question and methodology. Only then the behaviours occur natural and have predictive value for social interactions in real life.

With kind regards,
Wolf-Gero Lange
Behavioural Science Institute
Radboud University

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PARTICIPANT INFORMATION (For Experiment 2 Chapter 5)

Virtual Reality Study

Thank you for your interest in this study. You are invited to take part in a research project conducted at the School of Psychology at the University of East Anglia. Before you decide whether to take part in this study, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully. Email the researchers if there is anything that is not clear or if you would like more information. Take your time to decide whether you wish to take part or not.

What is this research looking at? The purpose of the study is to investigate how people behave in virtual social interactions and how individual differences influence these behaviours in a virtual reality (VR) environment. This study has three parts: online survey, lab experiment and short online task.

Why have I been invited to take part? You have been invited because you responded to an advert for this study. To take part, you need to be over 18 years old.

Do I have to take part? No. It is up to you to decide whether you want to take part or not. Please read this information sheet to help you decide. You can also ask questions about the study before deciding by emailing the principal researcher.

What will happen if I agree to take part? The first phase of this study will last approximately 10 minutes and will take place online at the lab on a laptop. You will respond to several questionnaires about social interactions you have (such as social relationships) and how you feel about them, and negative feelings you might experience (your general mood) such as anxiety. Then you will wear VR headset and enter an environment for 5-8 minutes. Once it is finished, you will join a short task online where you see several questions regarding your VR experience at the lab.

Will it help me if I take part? There will be no direct benefit to you from taking part in this research. However, you will be reimbursed with 3 SONA credit.

How will you store the information that I give you? All information which you provide during the study will be stored in accordance with the 2018 General Data Protection Regulation and kept strictly confidential. The chief investigator will be the custodian of the anonymous research data. We will not collect or store any identifiable data. All anonymised data and results will be stored for 10 years in order to comply with open practice standards. The electronic data will be stored on the university secure

Research Storage Infrastructure, based on IBM enterprise grade Storage Area Network hardware housed in secure, controlled and monitored data centres. Data will be regularly and automatically backed up to tape with on-site and off-site copies.

How will the data be used? Findings and anonymised research results that arise from the data will potentially be presented at conferences and published in peer-reviewed scientific journals. Before that time, we may make the results available as a preprint on bioRxiv (https://www.biorxiv.org) where new scientific results are often first reported. The anonymised data may be made available to the worldwide scientific community by hosting it on a public website (e.g., OSF or GitHub) to promote transparency in science and to facilitate its potential use in future research by other research groups.

What happens if I agree to take part but change my mind later? You have the right to withdraw at any time during the study and ask us to not use your data within two weeks after your participation.

How do I know that this research is safe for me to take part in? Although every reasonable effort will be taken to prevent breaches of confidentiality and protect the data we collect, confidentiality during actual Internet communication procedures cannot be guaranteed. However, we will take steps to mitigate as much of this risk as possible by only having access to fully anonymized data which is stored on password protected servers at the University of East Anglia. We will not collect or store any data that can identify you (e.g., your email address or IP address).

In addition, it is possible that your answers to some of the questionnaires evoke worries about your health. However, these are no diagnostic tools, and individual scores do not allow any such interpretation. Since scores are calculated after the data collection is finished, but your data is anonymized at the point of your participation, we will not be able to give you any feedback on your scores. Yet, if you should keep worrying, you should contact your family practitioner and see if s/he shares your concerns.

This research has been approved by the Psychology Research Ethics Committee on 6 September 2023 (ETH2324-0804). All research in the University is looked at by an independent group of people, called a Research Ethics Committee, to protect your safety, rights, wellbeing and dignity.

Contact details If you have a concern about any aspect of this study, please speak to Ceyda Kiyak (C.Kiyak@uea.ac.uk) or their supervisor, Dr Sara Bengtsson (S.Bengtsson@uea.ac.uk) and we will do our best to answer your query. If you remain unhappy or wish to make a formal complaint, please contact the Psychology Ethics Committee at the University of East Anglia who will seek to resolve the matter.

Ceyda Kiyak C.Kiyak@uea.ac.uk
Dr Sara Bengtsson S.Bengtsson@uea.ac.uk
Dr Gareth Edwards Stephen.G.Edwards@uea.ac.uk
School of Psychology Ethics Committee: ethics.psychology@uea.ac.uk
Head of School Professor Neil Cooper: neil.cooper@uea.ac.uk

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PARTICIPANT INFORMATION (For Study in Chapter 6)

Interactions in Virtual Reality Environment

Thank you for your interest in this study. You are invited to take part in a research project conducted at the School of Psychology at the University of East Anglia. Before you decide whether to take part in this study, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully. Email the researchers if there is anything that is not clear or if you would like more information. Take your time to decide whether you wish to take part or not.

What is this research looking at? The purpose of the study is to investigate how people behave in social interactions and how individual differences influence these behaviours. This study has three parts: online survey, lab experiment and a short online survey after the VR experiment.

Why have I been invited to take part? You have been invited because you responded to an advert for this study. To take part, you need to be over 18 years old and fluent in English.

Do I have to take part? No. It is up to you to decide whether you want to take part or not. Please read this information sheet to help you decide. You can also ask questions about the study before deciding by emailing the principal researcher (Ceyda Kiyak: C.Kiyak@uea.ac.uk).

What will happen if I agree to take part? You will be invited to the VR lab on UEA campus. Upon arrival, you will be asked to fill out some questionnaires on a computer. The online survey will last approximately 10 minutes. You will respond to several questionnaires about social interactions you have (such as social relationships) and how you feel about them, and negative feelings you might experience (your general mood) such as anxiety. Then you will watch a short video regarding the HRV device (a strap that monitors your Heart Rate Variability) that will be attached just below the chest during the VR experience. Next, you will wear the VR headset and HRV device (with this preparation expected to take around 8 minutes) and enter a virtual environment for 5-8 minutes where you will be given several instructions. At the end, you will be asked to complete a short online survey on a computer. The study is expected to take approximately 30-40 minutes.

Will it help me if I take part? There will be no direct benefit to you from taking part in this research. However, you will be reimbursed with £5 for your participation.

How will you store the information that I give you? All information which you provide during the study will be stored in accordance with the 2018 General Data Protection Regulation and kept strictly confidential. The chief investigator will be the custodian of the anonymous research data. We will not collect or store any identifiable data. All anonymised data and results will be stored for 10 years in order to comply with open practice standards. The electronic data will be stored on the university secure Research Storage Infrastructure, based on IBM enterprise grade Storage Area Network (SAN) hardware housed in secure, environmentally controlled and monitored data centres. Data will be regularly and automatically backed up to tape with on-site and off-site copies.

How will the data be used? Findings and anonymised research results that arise from the data will potentially be presented at conferences and published in peer-reviewed scientific journals. Before that time, we may make the results available as a preprint on bioRxiv (https://www.biorxiv.org) where new scientific results are often first reported. The anonymised data may be made available to the worldwide scientific community by hosting it on a public website (e.g., OSF or GitHub) to promote transparency in science and to facilitate its potential use in future research by other research groups.

What happens if I agree to take part, but change my mind later? You have the right to withdraw at any time during the study and ask us to not use your data within two weeks after your participation.

How do I know that this research is safe for me to take part in? Although every reasonable effort will be taken to prevent breaches of confidentiality and protect the data we collect, confidentiality during actual Internet communication procedures cannot be guaranteed. However, we will take steps to mitigate as much of this risk as possible by only having access to fully anonymized data which is stored on password protected servers at the University of East Anglia. We will not collect or store any data that can identify you.

In addition, it is possible that your answers to some of the questionnaires evoke worries about your health. However, these are no diagnostic tools, and individual scores do not allow any such interpretation. Since scores are calculated after the data collection is finished, but your data is anonymized at the point of your participation, we will not be able to give you any feedback on your scores. Yet, if you should keep worrying, you should contact your family practitioner and see if s/he shares your concerns.

This research has been approved by the Psychology Research Ethics Committee on 24 December 2023 (ETH2324-1222). All research in the University is looked at by an independent group of people, called a Research Ethics Committee, to protect your safety, rights, wellbeing and dignity.

Contact details

If you have a concern about any aspect of this study, please speak to Ceyda Kiyak (C.Kiyak@uea.ac.uk) or their supervisor, Dr Sara Bengtsson (S.Bengtsson@uea.ac.uk). Dr Gareth Edwards (Stephen.G.Edwards@uea.ac.uk) will do our best to answer your

query. If you remain unhappy or wish to make a formal complaint, please contact the Psychology Ethics Committee at the University of East Anglia who will seek to resolve the matter as soon as possible.

Ceyda Kiyak C.Kiyak@uea.ac.uk
Dr Sara Bengtsson S.Bengtsson@uea.ac.uk
Dr Gareth Edwards Stephen.G.Edwards@uea.ac.uk
School of Psychology Ethics Committee: ethics.psychology@uea.ac.uk
Head of School Professor Neil Cooper: neil.cooper@uea.ac.uk

Consent (for Experiment 2 in Chapter 5 and Study in Chapter 6)

Please read the following declarations and check each box if you understand and agree with it.

- I have read and understand the participant information.
- I have had opportunity to ask questions about the study, and if I did, I have received satisfactory answers to these questions.
- I understand I can withdraw from the study at any point before, during, or after the study without penalty.
- I understand this study has been reviewed and received ethics clearance through the University of East Anglia Ethics Committee.
- I understand that the researchers will not collect any data that could directly identify me.
- I understand that this research will be written up and published.
- I agree for the research data collected in this study to be deposited in open access archives so that it may be used in other research studies.
- I understand that any data that leave the research group and/or is published will be anonymized.
- I understand how to raise a concern and make a complaint.
- I agree to take part in this study.

Debriefing (for Experiment 2 in Chapter 5 and Study in Chapter 6)

Thank you for participating in this study. If you think you may need any well-being support, we encourage you to contact a relevant support service for free and confidential help.

NHS talking therapies: https://www.england.nhs.uk/mental-health/adults/nhs-talking-therapies/

SHOUT: https://giveusashout.org/ Text 'SHOUT' to 85258 for 24/7 mental health support

Red Cross: https://www.redcross.org.uk/get-help/get-help-with-loneliness

Mind: https://www.mind.org.uk/

Researcher: Ceyda Kiyak (C.Kiyak@uea.ac.uk)

Supervisor: Dr Sara Bengtsson (S.Bengtsson@uea.ac.uk)

Supervisor: Dr Gareth Edwards (Stephen.G.Edwards@uea.ac.uk)

Do also contact us if you have any worries or concerns about this research.

School of Psychology Ethics Committee: ethics.psychology@uea.ac.uk Phone 01603 597146

Head of School Professor Neil Cooper: neil.cooper@uea.ac.uk Phone 01603 592996

Appendix B

Participant Recruitment Posters

i. Poster for Experiment 1 and 2 in Chapter 4 (Adolescent only)

ii. Poster for VR Poster Experiment 2 in Chapter 5

iii. Poster for the VR Pub Experiment in Chapter 6

Appendix C

VR POSTER PROTOCOL

Virtual Reality Experiment Protocols

The Day of the Experiment - Before Each Participant:

1. Arrive 20 minutes early to the lab.

2. Prepare VR equipment:

- Make sure the correct headset is plugged into the computer (white headset), small USB cable needs to be plugged in, and another smaller cable underneath, make sure switch of on at the wall.
- Make sure headset is on the cross on floor when logging into the computer.
- Turn on headset, make sure blue or green/yellow light is on.
- On PC: **Run Picolink, start DP Connection** (use headset/controller to select start boundary, then click start DP connection).
- If the VR headset is not connected, connect using the button on the side of the headset = then should see room in black and white, should see blue/green circle around you in VR, and should say 'retrieve play boundary' = select small.
- **Launch SteamVR program**
- STEAMVR 2.3.5. You need to see static green line (if it is pink it is not working), click three lines left top side, select room setup, select standing only, then calibrate centre, calibrate floor (cm), make sure select cm (put headset on floor), setup should be complete, make sure controller is switched off before the experiment is started (when controller is grey on the screen, it is switched off), then start experiment up, (**BBVR23**)
- If (on the headset), you see a SteamVR menu overlay, use a controller to tap 'A' while pointing away from it. If the controller is not active, press any controller buttons until it appears in the scene.
- Ensure sensors and headset are visible in **STEAM app**.

- Check if everything is working. (Run through the experiment to test).
- Clean VR lenses with cloth.

After Participant Arrival:

1. Direct participant to the VR lab, allocate a space for belongings, and ensure pockets are light.

2. Silence phones.

3. Qualtrics: Survey needs to be completed on Qualtrics.

- Type in participant code (P_XXXXXX).
- Enter participant number (chronological order).

Experiment Setup Explanation (You will read it to the participant):

- Briefly explain the experiment structure.
- Mention VR experience, headset usage, and experiment duration (5-8 min).
- Ask about motion sickness and address participant questions.
- **Ready only green highlighted sentences to the participant.**
- "You will be in an international conference setting; you have a poster on your right. The content of the poster is not important. You do not have to talk about the poster. You are standing in front of a door and will have people coming to you, they will come up to you and look at your poster for a brief moment. What you need to do is to look at their eye colours. The possible eye colours are **brown, green, and blue.** You need to report this to us, by saying it out loud after each agent has left or turned to the side to leave. Try not to ask questions and don't move your head or body. Just say your answer out loud. Remember to look ahead while saying the eye colours. We will listen but not respond to your answers about eye colours."

VR Headset Setup:

- "You can wear the headgear to test it out first".
- Put on the headgear, adjust it and ask if they are comfortable.
- Let them get used to the virtual environment, walk around.
- "Look straight AHEAD of you."
- We can adjust the tightness to make the vision sharper; try to move it and we will readjust it.

- "Please walk towards the yellow point and now look down to see if it is below you. Try not to touch or adjust the headset in the middle of the trial. Do not turn towards the poster during the trial. Do not make hand or body movements. Please do not talk during the trial except for saying the eye colour. Please Say it LOUD and CLEAR. Now put their hands on the side with a RELAXED posture.".
- **Notebook and pen:** Prepare the notebook to note down and actually note it down during the experiment when they say the eye colour.

Start the Experiment

- Go to the VR program ("BBVR23"), click start (make sure you have entered the correct participant ID first. Check the excel sheet to see the last participant ID)
- Inform the participant.
- Click **Recalibration.**
- "You will start with baseline measurement first for the first 20 seconds."
- Click **START BASELINE.**
- "Focus on the yellow cube"
- Once baseline is finished, tell them that the experiment is about to start.
- Again, make sure that they are standing correctly = hands by their side, don't want them to touch the headset, don't let them move/sway their body.
- Take the notebook and pen so they can see that you have it.
- "Now we will start the experiment, look straight at the door, the agents will come from the door, one by one. Please tell me the eye colour **OUT LOUD**, I will not respond to you. You should not speak until the experiment finished."
- Click **START TRIAL.**
- Wait until the last agent (16^{th}) leave the virtual environment (UEA experiment only).
- Click escape button on keyboard to finish experiment.
- Once the experiment is over: "I will take the headset off. Do you feel okay/if they feel dizzy?".

After Each Participant:

- Add on the excel sheet (Logs -> Notes), if there are any comments about the participant (e.g., "they moved around a lot").
- Reimburse participants on SONA.

VR PUB PROTOCOL

The Day of the Experiment

Before Participants Arrive:

1. Arrive 20 minutes early to the lab.

2. Prepare VR Hardware:

- **PC Setup**
  - Turn on headset, make sure blue or green/yellow light is on.
  - Set audio output to "Speakers (AC Interface)"
    - Open Sound Settings (Right-click the volume icon in the bottom right, then click "Sound Settings")
- **HRV (Heart Rate Variability) Connection Setup**
  - The HRV band should be kept in the same cupboard it was found in
  - Make sure the HRV is connected (check Bluetooth settings). If it is not paired, you may need to wear the band to turn the device on.

3. Prepare VR Software

- **Launch SteamVR program**
  - Scan the QR code on the phone to log in
- **Run Picolink, click start DP Connection**
  - In VR headset: use controller to select start boundary, then start DP connection.
- **Run Open HRV**
  - Click Scan
  - It will say 'searching for devices. The device will appear in the drop-down box in the bottom left (to the right of the 'scan' button).
  - Once you see "found 1 sensor" in the bottom left, click Connect.
  - You should now see two active graphs: a blue line on the top, and a graph starting on the right side in a colourful gradient

- **Start experiment program**
    - You should be able to see heart rate in the bottom left corner (if not, please double check the Open HRV step).
    - You should see the POV (point of view) from the floor. If the camera is above the floor, reset the room setup in Steam VR (see Troubleshooting).
- **Final Checks**
    - Ensure sensors and headset are visible in **SteamVR app**.
    - Check everything is working. (Run through the experiment to test).
    - Clean VR lenses with cloth.

After Participant Arrival:

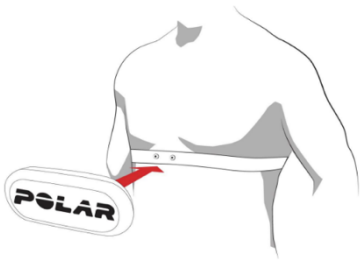
1. Direct participant to the Vision and Action (V&A) lab, allocate a space for belongings, and ensure pockets are light.

2. Silence phones.

Qualtrics Survey: Make sure the participant reads and complete the online survey first before starting the experiment or highlight important things (questions about interactions with others and emotions, VR motion sickness, anonymous data collection, HRV device and gel).

Put HRV Monitor on Participant

- Explain that the device needs to be worn, and they will put it on themselves in the changing room." Your heart rate will be measured through this band attached to your waist and I need you to watch this video to see how you can do it. You can use this changing room to have some privacy."
- Make sure the HRV graph looks realistic (i.e. no wild spikes). Wait for a minute or so. Lead Researcher will give a signal to Assistant Researcher when things are ready.



Experiment Trials:

Enter participant number and then give the instruction
Please talk very slowly and clearly, and don't rush this whole section

Task 1 (stopwatch time limit 60s):
"Now you we are going to start the VR experience which will last around 6-8 minutes. You will have four short trials. I will give you instructions on what to do.
During the whole study we will not be responding to you if you talk to us. But if you feel any discomfort, please let me know. During the VR experience, I will hold this cable so you can walk freely. There will be a virtual wall in the environment to protect you bumping into things in the room. If you are ever about to bump into anything, I will tell you to stop for your safety. So, when I say stop, please stop.
So now, you'll enter a pub with background noise and music.
Right, now you can wear the headgear to test it out first".
put the headset on
"Just walk around and explore for the next a minute".
"Are you ready?".
"And now go back to the yellow starting point and stand facing the bar".
Calibrate height

Task 2:
"Now there will be other people on both sides of the pub. Choose one of the sides where you feel most comfortable and hang out there for some time".
"Are you ready?".
PRESS NEXT
"Now walk back to your yellow starting point and stand facing the bar".

Task 3:
"And now, some of the people in the pub will be having a conversation on your left. Try to listen to their conversation (the closer you are, the better you'll hear). Once you hear the bell sound, walk back to your yellow starting point".
"Are you ready?".

Task 4:
"Now this time you can join the group on your left having a conversation - join in with them by talking, nodding, laughing etc. But remember they will not be responding to you. Once you hear the bell sound, walk back to your yellow starting point ".
"Are you ready?".
when the participant is back to the line, click next again to end experiment
take-off the HRV device (and offer them some tissue to clean the gel)

VR experience survey: "Now, we need you to complete one final very short questionnaire about your experience in the VR environment"

Give them "Debriefing sheet.

Appendix D

Questionnaires and Scales

Sociodemographic Questionnaire

Biological sex
- Female
- Male

Age: _____

What school year are you in? (for adolescents) _____

Education (for adults)
- Primary school
- Middle school
- High school
- Bachelor's degree
- Master's degree
- PhD

Employment status:
- Full-time employment
- Part-time employment
- Self-employed
- Unemployed
- Homemaker
- Student
- Retired
- Other

Relationship status:
- Single
- In a relationship
- Married
- Separated
- Divorced

Living condition (for adolescents)

- Alone
- With friends or shared house
- With parents
- With other family members
- Other (please specify): _____

Living condition (for adults)

- Alone
- Shared house
- With family
- With partner
- With husband or wife
- Other (please specify): _____

Ethnicity:

- White
- Gypsy or Traveller
- Black or Black British – Caribbean
- Black or Black British – African
- Asian or Asian British – Indian
- Asian or Asian British – Pakistani
- Asian or Asian British – Bangladeshi
- Chinese
- Mixed - White and Black Caribbean
- Mixed - White and Black African
- Mixed - White and Asian
- Arab
- Any Other Ethnic Background

The Loneliness and Social Dissatisfaction Questionnaire for Adolescents (LSDQ; Cassidy & Asher, 1992)

Instruction: Please indicate how often you felt this way IN THE LAST YEAR.
(1) Never
(2) Rarely
(3) Sometimes
(4) Often
(5) Very Often

	ITEMS
1	I felt alone.
2	I felt left out of things.
3	I was lonely.
4	School was a lonely place for me.
5	I was sad and alone.

The Short Mood and Feelings Questionnaire for Adolescents (SMFQ; Angold et al., 1987)

Instruction: This form is about how you might have been feeling or acting recently. For each question, please check how much you have felt or acted this way in the past two weeks.
(0) Not true
(1) Sometimes
(2) True

	ITEMS
1	I felt miserable or unhappy.
2	I didn't enjoy anything at all.
3	I felt so tired I just sat around and did nothing.
4	I was very restless.
5	I felt I was no good anymore.
6	I cried a lot.
7	I found it hard to think properly or concentrate.
8	I hated myself.
9	I was a bad person.
10	I felt lonely.
11	I thought nobody really loved me.
12	I thought I could never be as good as other kids.
13	I did everything wrong.

Social Anxiety Scale for Adolescents (SAS-A; La Greca & Lopez, 1998)

Instruction: Indicate how much the following statements apply to you.
(1) Not true
(2) Rarely
(3) Sometimes
(4) True
(5) Always true

	ITEMS
1	I worry about what others say about me.
2	I worry about what others think of me.
3	I feel that others make fun of me.
4	I get nervous when I meet new people.
5	I feel shy around people I don't know.
6	I worry about doing something in front of others.
7	I am quiet when I'm with a group of people.
8	I feel shy even with peers I know very well.

Toronto Alexithymia Scale for Adolescents (TAS-20; Bagby et al., 1994)

Instruction: Indicate how true the statements below are for you.
(1) Not true
(2) Sometimes true
(3) Often true

	ITEMS
1	I am often confused about the way I am feeling inside.
2	I find it difficult to say how I feel inside.
3	I feel things in my body that even doctors don't understand.
4	I can easily say how I feel inside.
5	When I have a problem, I want to know where it comes from and not just talk about it.
6	When I am upset, I don't know if I am sad, scared, or angry.
7	I am often puzzled by things that I feel in my body.
8	I'd rather wait and see what happens instead of thinking about why things happen.
9	Sometimes I can't find the words to say how I feel inside.
10	It is important to understand how you feel inside.
11	I find it hard to say how I feel about other people.
12	Other people tell me that I should talk more about how I feel inside.

13	I don't know what's going on inside me.
14	I often don't know why I am angry.
15	I prefer talking to people about everyday things rather than about how they feel.
16	I prefer watching funny television programs rather than films that tell a story about other people's problems.
17	It is difficult for me to say how I really feel inside, even to my best friend.
18	I can feel close to someone, even when we are sitting still and not saying anything.
19	Thinking about how I feel helps me when I want to do something about my problems.
20	When I have to concentrate on a film to understand the story, I enjoy the film much less.

The Loneliness Scale (UCLA; Russel, 1996)

Instruction: Indicate how often each of the statements below is descriptive of you.

(1) Never
(2) Rarely
(3) Sometimes
(4) Often

	ITEMS
1	How often do you feel that you are 'in tune' with the people around you?
2	How often do you feel that you lack companionship?
3	How often do you feel that there is no one you can turn to?
4	How often do you feel alone?
5	How often do you feel part of a group of friends?
6	How often do you feel you have a lot in common with the people around you?
7	How often do you feel that you are no longer close to anyone?
8	How often do you feel your interests/ideas are not shared by those around you?
9	How often do you feel outgoing and friendly?
10	How often do you feel close to people?
11	How often do you feel left out?
12	How often do you feel that your relationships with others are not meaningful?
13	How often do you feel that no one really knows you well?
14	How often do you feel isolated from others?
15	How often do you feel you can find companionship when you want it?
16	How often do you feel that there are people who really understand you?
17	How often do you feel shy?
18	How often do you feel that people are around you but not with you?
19	How often do you feel that there are people you can talk to?
20	How often do you feel that there are people you can turn to?

The Depression Scale (Ces-D; Radloff, 1977)

Instruction: Please read each question carefully, then circle one of the numbers to indicate how you felt or behaved during the past week, including today.

(0) Rarely or none of the time (less than 1 day)
(1) Some or little of the time (1-2 days)
(2) Occasionally or moderate amount of the time (3-4 days)
(3) Most or all of the time (5-7) days

	ITEMS
1	I was bothered by things that usually don't bother me.
2	I had trouble keeping my mind on what I was doing.
3	I felt depressed.
4	I felt that everything I did was an effort.
5	I felt hopeful about the future.
6	I felt fearful.
7	My sleep was restless.
8	I was happy.
9	I felt lonely.
10	I could not get 'going.'

Social Interaction Anxiety-6 (SIAS-6; Peters et al., 2012)

Instructions: In this section, for each item, please circle the number to indicate the degree to which you feel the statement is characteristic or true for you.

(0) Not at all
(1) Slightly
(2) Moderately
(3) Very
(4) Extremely

	ITEMS
1	I have difficulty making eye contact with others.
2	I find it difficult to mix comfortably with the people I work with.
3	I tense up if I meet an acquaintance in the street.
4	I feel tense when I am alone with just one person.
5	I have difficulty talking with other people.
6	I find it difficult to disagree with another's point of view.

The Social Phobia Scale (SPIN; Connor et al., 2000)

Instructions: Please read each statement and click in the column that indicates how much the statement applied to you over the past week.

(1) Not at all
(2) A little bit
(3) Somewhat
(4) Very much
(5) Extremely

	ITEMS
1	I am afraid of people in authority.
2	I am bothered by blushing in front of people.
3	Parties and social events scare me.
4	I avoid talking to people I don't know.
5	Being criticized scares me a lot.
6	I avoid doing things or speaking to people for fear of embarrassment.
7	Sweating in front of people causes me distress.
8	I avoid going to parties.
9	I avoid activities in which I am the centre of attention.
10	Talking to strangers scares me.
11	I avoid having to give speeches.
12	I would do anything to avoid being criticized.
13	Heart palpitations bother me when I am around people.
14	I am afraid of doing things when people might be watching.
15	Being embarrassed or looking stupid are among my worst fears.
16	I avoid speaking to anyone in authority.
17	Trembling or shaking in front of others is distressing to me.

The Alexithymia Scale (TAS-20; Bagby et al., 1994)

Instructions: Please read each statement and indicate how much you agree or disagree with the statement.

(1) Strongly disagree
(2) Disagree
(3) Neutral
(4) Agree
(5) Strongly agree

	ITEMS
1	I am often confused about what emotion I am feeling.
2	It is difficult for me to find the right words for my feelings.
3	I have physical sensations that even doctors don't understand.
4	I am able to describe my feelings
5	I prefer to analyse problems rather than just describe them.
6	When I am upset, I don't know if I am sad, frightened, or angry.
7	I am often puzzled by sensations in my body.
8	I prefer to just let things happen rather than to understand why they turned out that way.
9	I have feelings that I can't quite identify.
10	Being in touch with emotions is essential.
11	I find it hard to describe how I feel about people.
12	People tell me to describe my feelings more.
13	I don't know what's going on inside me.
14	I often don't know why I am angry.
15	I prefer talking to people about their daily activities rather than their feelings.
16	I prefer to watch 'light' entertainment shows rather than psychological dramas.
17	It is difficult for me to reveal my innermost feelings, even to close friends.
18	I can feel close to someone, even in moments of silence.
19	I find examination of my feelings useful in solving personal problems.
20	Looking for hidden meanings in movies or plays distracts from my enjoyment.

Brief Negative Evaluation Scale (Leary, 1983)

Instruction: Read each of the following statements carefully and indicate how characteristic it is of you according to the following scale.

0 = Not at all characteristics of me

1 = Slightly characteristic of me

2 = Moderately characteristic of me

3 = Very characteristic of me

4 = Extremely characteristic of me

	ITEMS
1	I worry about what other people will think of me even when I know it doesn't make any difference.
2	I am frequently afraid of other people noticing my shortcomings.
3	I am afraid others will not approve of me.

4	I am afraid that people will find fault with me.
5	When I am talking to someone, I worry about what they may be thinking about me.
6	I am usually worried about what kind of impression I make.
7	Sometimes I think I am too concerned with what other people think of me.
8	I often worry that I will say or do the wrong things.

Patient Health Questionnaire (PHQ-8; Kroenke et al., 2009)

Instruction: Over the last two weeks, how often have you been bothered by any of the following problems?

(1) Not at all

(2) Several days

(3) More than half days

(4) Nearly every day

	ITEMS
1	Little interest or pleasure in doing things.
2	Feeling down, depressed, or hopeless.
3	Trouble falling or staying asleep or sleeping too much.
4	Feeling tired or having little energy.
5	Poor appetite or overeating.
6	Feeling bad about yourself – or that you are a failure or have let yourself or your family down.
7	Trouble concentrating on things, such as reading the newspaper or watching television.
8	Moving or speaking so slowly that other people could have noticed? Or the opposite – being so fidgety or restless that you have been moving around a lot more than usual.

General Trust Scale (Yamagishi & Yamagishi, 1994)

Using the following scale, please indicate how much you agree or disagree with the following statements.

(1) Strongly agree
(2) Disagree
(3) Neutral
(4) Agree
(5) Strongly agree

	ITEMS
1	Most people are basically honest.
2	Most people are trustworthy.
3	Most people are basically good and kind.
4	Most people are trustful of others.
5	I am trustful.
6	Most people will respond in kind when they are trusted by others.

Cognitive-Behavioural Avoidance Scale (CBAS; Ottenbreit & Dobson, 2004)

Instruction: Different people use different strategies to deal with situations and problems in their lives. Below are a number of strategies that people may use to deal with situations and problems. Please read each statement carefully and indicate how true, in general, each statement is for you using the following key:

1 = Not at all true for me
2 = Somewhat true for me
3 = Moderately true for me
4 = Very much true for me
5 = Extremely true for me

SUBSCALE	NUMBER	ITEM
COGNITIVE NONSOCIAL	4	I fail to do what is needed to follow through with achievement goals I have set for myself.
	5	In order to avoid feelings of disappointment, I just not to get too serious about work/school.
	7	I choose to turn down opportunities to further my education/career.

	11	I think to myself that I will not be able to complete really challenging tasks.
	18	I do not try to think about ways to improve my work/school performance.
	25	I avoid making decisions about my future.
	26	When I experience confusion in my relationships, I do not try to figure things out.
	27	While I know that I have to make some important decisions about school/work, I just do not get down to it.
	29	I distract myself when I start to think about my work/school performance.
	31	I find myself avoiding tasks and assignments that are really important.
COGNITIVE SOCIAL	10	I try not to think about problems in my personal relationships.
	12	While I know I should make decisions about my personal relationships, I just let things go on as they are.
	16	I fail to discuss/address tension that builds in a friendship.
	20	I just wait out tension in my relationships hoping that it will go away.
	22	There is nothing I can do to improve problems in my relationships.
BEHAVIOURAL NONSOCIAL	6	Rather than try new activities, I tend to stick with the things I know.
	7	I choose to turn down opportunities to further my education/career.
	9	I quit activities that challenge me too much.
	11	I think to myself that I will not be able to complete really challenging tasks.
	13	I avoid trying new activities that hold the potential for failure.
	28	Rather than getting out and doing things, I just sit at home and watch TV.
BEHAVIOURAL SOCIAL	1	I avoid attending social activities.
	8	I do not answer the phone in case people are calling with social invitations.
	14	I do not go out to events when I know there will be a lot of people I do not know.
	15	Instead of thinking about problems in my social life, I tell myself that I prefer to be alone.
	17	I find that I often want to leave social gatherings.

21	I tend to make up excuses to get out of social activities.
23	I turn down opportunities to socialize with the opposite sex.
24	I tend to remain to myself during social gatherings or activities.

VR Presence Questionnaire Scale

Instruction: Here are several suggestions that may apply to the experience you have just had in the VR environment. Please indicate whether or not each of these propositions applies to your experience. There is no right or wrong answer, only your opinion is important. Remember that you should answer these questions based only on the experience you just had.

	FACTOR	ITEM		COPYRIGHT
1	**Sense of presence**	In the computer-generated world I had a sense of 'being there'.	Not At All – Very much	Slater & Usoh, 1994
2		Somehow, I felt that the virtual world surrounded me.	Fully disagree - Fully agree	
3		I felt like I was just perceiving pictures.	Fully disagree - Fully agree	
4		I did not feel present in the virtual space.	Did not feel - Felt present	
5		I had a sense of acting in the virtual space, rather than operating something from outside.	Fully disagree - Fully agree	
6		I felt present in the virtual space.	Fully disagree - Fully agree	
7	**Sense of involvement**	How aware were you of the real world surrounding while navigating in the virtual world?	Extremely aware – not aware at all	Witmer & Singer, 1994
8		I was not aware of my real environment.	Fully disagree - Fully agree	
9		I still paid attention to the real environment.	Fully disagree - Fully agree	

10		I was completely captivated by the virtual world.	Fully disagree - Fully agree	
11	**Sense of realism**	How real did the virtual world seem to you?	Completely real – Not real at all	Hendrix, 1994
12		How much did your experience in the virtual environment seem consistent with your real-world experience?	Not consistent Very consistent	Witmer & singer, 1994
13		The virtual world seemed more realistic than the real world.	Fully disagree - Fully agree	

Appendix E

Virtual Reality Data Experiments Data Preprocessing Procedure and R Coding

CHAPTER 5 – VR Poster Data Preprocessing

In these two experiments each participant:

- Completed 12 trials for the Experiment 1 at RU and 16 trials for the Experiment 2 at UEA.
- Stood on a marked spot while a virtual agent approached them from 6m to 1m.
- Head position was tracked via posz (z-axis = forward/backward).

Data Columns Used

COLUMN	DESCRIPTION
POSZ	Participant's position along the Z-axis (forward–backward)
AGENT_DIST	Distance of the VR agent from the participant
TRIAL	Trial number (1–12 or 1-16)
PID	Participant ID
EXPRESSION	Emotion shown by the virtual agent (e.g., happy)

DATA PROCESSING FOR AMPLITUDE

STEP 1: Baseline Posture (baseline_posz)

I took the first 30 frames of each trial (≈2 seconds), before the agent gets close, and averaged the posz value.

Baseline Calculation (baseline_posz)

Average of the first 30 frames per trial.

R Coding for Baseline

```
library(dplyr)
library(readr)
library(purrr)

data_folder <- "~/Desktop/RU VR DATA"
file_list <- list.files(data_folder, full.names = TRUE, pattern =
"\\.tsv$")
```

```
compute_baseline <- function(file_path) {
  message("Processing: ", basename(file_path))
  df <- tryCatch({
    read_tsv(file_path, show_col_types = FALSE)
  }, error = function(e) return(tibble()))

  if (!all(c("trial", "posz", "pid", "expression") %in% names(df))) {
    message("Skipping file due to missing columns: ", basename(file_path))
    return(tibble())
  }

  df <- df %>%
    mutate(trial = suppressWarnings(as.numeric(trial)),
           posz = as.numeric(posz)) %>%
    filter(!is.na(trial))

  df %>%
    group_by(trial) %>%
    slice_head(n = 30) %>%
    summarise(baseline_posz = mean(posz, na.rm = TRUE),
              pid = first(pid),
              expression = first(expression),
              .groups = "drop") %>%
    mutate(file = basename(file_path))
}

baseline_data <- map_dfr(file_list, compute_baseline)
write.csv(baseline_data, "~/Desktop/Amplitude_Baseline_PosZ.csv", row.names
= FALSE)
```

STEP 2: Leaning Forward (leaning_forward)

1. First, I found the first frame where agent_dist <= 1 (agent is closest).
2. Took the 47-frame window: 16 frames (1 second) before agent distance = 1m + 31 (2 second) after before agent distance = 1m (in total 3 seconds=47 frames)
3. Extracted the maximum posz value → strongest lean forward.

Leaning Forward (leaning_forward)

Maximum posz within 47-frame window centered on agent_dist <= 1.

R Coding for Leaning Forward

```
library(dplyr)
library(readr)
library(purrr)

data_folder <- "~/Desktop/RU VR DATA"
file_list <- list.files(data_folder, full.names = TRUE, pattern =
"\\.tsv$")

compute_leaning_forward <- function(file_path) {
  message("Processing: ", basename(file_path))
  df <- tryCatch({
```

```
    read_tsv(file_path, show_col_types = FALSE)
  }, error = function(e) return(tibble()))

  if (!all(c("trial", "posz", "agent_dist", "expression", "pid") %in%
names(df))) {
    message("Skipping file due to missing columns: ", basename(file_path))
    return(tibble())
  }

  df <- df %>%
    mutate(trial = suppressWarnings(as.numeric(trial)),
           posz = as.numeric(posz),
           agent_dist = as.numeric(agent_dist)) %>%
    filter(!is.na(trial))

  df %>%
    group_by(trial) %>%
    group_modify(~{
      trial_df <- .x
      anchor_index <- which(trial_df$agent_dist <= 1)[1]
      if (is.na(anchor_index) || anchor_index < 17 || (anchor_index + 30) >
nrow(trial_df)) return(tibble(leaning_forward = NA))
      window_df <- trial_df[(anchor_index - 16):(anchor_index + 30), ]
      tibble(
        pid = first(trial_df$pid),
        expression = first(trial_df$expression),
        leaning_forward = max(window_df$posz, na.rm = TRUE)
      )
    }) %>%
    ungroup() %>%
    mutate(file = basename(file_path))
}

leaning_forward_data <- map_dfr(file_list, compute_leaning_forward)
write.csv(leaning_forward_data, "~/Desktop/Leaning_Forward_PosZ.csv",
row.names = FALSE)
```

STEP 3: Leaning Backward (leaning_backward)

I used the same 47-frame window but extracted the minimum posz value → strongest lean backward.

Minimum posz in the same 47-frame window.

R Coding for Leaning Backward

```
library(dplyr)
library(readr)
library(purrr)

data_folder <- "~/Desktop/RU VR DATA"
file_list <- list.files(data_folder, full.names = TRUE, pattern =
"\\.tsv$")

compute_leaning_backward <- function(file_path) {
  message("Processing: ", basename(file_path))
  df <- tryCatch({
```

```
    read_tsv(file_path, show_col_types = FALSE)
  }, error = function(e) return(tibble()))

  if (!all(c("trial", "posz", "agent_dist", "expression", "pid") %in%
names(df))) {
    message("Skipping file due to missing columns: ", basename(file_path))
    return(tibble())
  }

  df <- df %>%
    mutate(trial = suppressWarnings(as.numeric(trial)),
           posz = as.numeric(posz),
           agent_dist = as.numeric(agent_dist)) %>%
    filter(!is.na(trial))

  df %>%
    group_by(trial) %>%
    group_modify(~{
      trial_df <- .x
      anchor_index <- which(trial_df$agent_dist <= 1)[1]
      if (is.na(anchor_index) || anchor_index < 17 || (anchor_index + 30) >
nrow(trial_df)) return(tibble(leaning_backward = NA))
      window_df <- trial_df[(anchor_index - 16):(anchor_index + 30), ]
      tibble(
        pid = first(trial_df$pid),
        expression = first(trial_df$expression),
        leaning_backward = min(window_df$posz, na.rm = TRUE)
      )
    }) %>%
    ungroup() %>%
    mutate(file = basename(file_path))
}

leaning_backward_data <- map_dfr(file_list, compute_leaning_backward)
write.csv(leaning_backward_data, "~/Desktop/Leaning_Backward_PosZ.csv",
row.names = FALSE)
```

STEP 4: Amplitudes (Relative Movement)

Amplitude quantified the change from baseline; it tells us how reactive participants were.

VARIABLE	FORMULA	INTERPRETATION
FORWARD_AMPLITUDE	leaning_forward – baseline_posz	Bigger = more approach
BACKWARD_AMPLITUDE	baseline_posz – leaning_backward	Bigger = more avoidance

Amplitude Calculation: Combines all data and calculates change from baseline.

R Code for Amplitude

```
library(dplyr)

baseline <- read.csv("~/Desktop/Amplitude_Baseline_PosZ.csv")
forward <- read.csv("~/Desktop/Leaning_Forward_PosZ.csv")
backward <- read.csv("~/Desktop/Leaning_Backward_PosZ.csv")

# Merge all by pid, trial, expression
merged <- baseline %>%
  inner_join(forward, by = c("pid", "trial", "expression")) %>%
  inner_join(backward, by = c("pid", "trial", "expression"))

# Compute amplitude variables
amplitude_data <- merged %>%
  mutate(
    forward_amplitude = leaning_forward - baseline_posz,
    backward_amplitude = baseline_posz - leaning_backward
  )

# Save final dataset
write.csv(amplitude_data, "~/Desktop/Amplitude_Final.csv", row.names =
FALSE)
```

Data Preprocessing for Velocity

General Steps

1. **Identifying the anchor (baseline) at 1 m**
    - For each participant × trial, I located the first time point when the agent reaches the fixed distance criterion (agent_dist ≤ 1 m).
    - Then recorded:
        - baseline_time = time at that moment
        - baseline_posz = pos-z at that same moment
2. **Defining the stationary phase window**
    - The data was restricted to the post-anchor period only, i.e., when the agent is no longer approaching.
    - Used a consistent duration window (e.g., 0–5 seconds after baseline_time).
3. **Extract peak and trough within the stationary window**
    - **Peak (approach):** maximum pos-z within the stationary window, with its timestamp (**peak_time**).

- **Trough (avoidance):** minimum pos-z within the stationary window, with its timestamp (**trough_time**).

4. **Compute displacement relative to baseline**
   - **Approach displacement** = peak_posz – baseline_posz
   - **Avoidance displacement** = trough_posz – baseline_posz
5. **Compute time-to-extreme**
   - **time_to_peak** = peak_time – baseline_time
   - **time_to_trough** = trough_time – baseline_time
6. **Calculate velocity (time-based, signed)**
   - **Approach velocity** = (peak_posz – baseline_posz) / time_to_peak
   - **Avoidance velocity** = (trough_posz – baseline_posz) / time_to_trough

Interpretation

- Larger **positive** approach velocity = faster forward lean (approach).
- More **negative** avoidance velocity = faster backward lean (avoidance).

R Code for Velocity Calculation

```
############################################################
# Velocity Calculation: Embodied Approach & Avoidance
# Author: (you)
# Purpose: Trial-level velocity metrics during stationary phase
############################################################

library(dplyr)
library(readr)
library(purrr)

#------------------------------------------------------------
# 0. File handling
#------------------------------------------------------------

data_folder <- "~/Desktop/RU VR DATA"
file_list <- list.files(data_folder, full.names = TRUE, pattern =
"\\.tsv$")

#------------------------------------------------------------
# 1. Core function
#------------------------------------------------------------

compute_velocity <- function(file_path) {

  message("Processing: ", basename(file_path))
```

```
#-----------------------------
# Read file safely
#-----------------------------
df <- tryCatch(
  read_tsv(file_path, show_col_types = FALSE),
  error = function(e) return(tibble())
)

#-----------------------------
# Column sanity check
#-----------------------------
required_cols <- c(
  "pid", "trial", "time_sec",
  "posz", "agent_dist", "expression"
)

if (!all(required_cols %in% names(df))) {
  message("Skipping (missing columns): ", basename(file_path))
  return(tibble())
}

#-----------------------------
# Basic cleaning
#-----------------------------
df <- df %>%
  mutate(
    pid        = as.character(pid),
    trial      = as.numeric(trial),
    time_sec   = as.numeric(time_sec),
    posz       = as.numeric(posz),
    agent_dist = as.numeric(agent_dist)
  ) %>%
  filter(!is.na(trial), !is.na(time_sec), !is.na(posz))

#-------------------------------------------------------------
# 2. Trial-wise processing
#-------------------------------------------------------------
df %>%
  group_by(pid, trial) %>%
  group_modify(~{

    trial_df <- .x

    #-----------------------------------
    # 2a. Identify baseline (agent hits 1 m)
    #-----------------------------------
    anchor_row <- trial_df %>%
      filter(agent_dist <= 1) %>%
      slice_min(time_sec, with_ties = FALSE)

    if (nrow(anchor_row) == 0) return(tibble())

    baseline_time <- anchor_row$time_sec[1]
    baseline_posz <- anchor_row$posz[1]

    #-----------------------------------
    # 3. Stationary phase (post-baseline)
    #-----------------------------------
    stationary_df <- trial_df %>%
      filter(time_sec >= baseline_time,
```

```
            time_sec <= baseline_time + 5)

    if (nrow(stationary_df) < 5) return(tibble())

    #-----------------------------------
    # 4. Peak & trough
    #-----------------------------------
    peak_idx   <- which.max(stationary_df$posz)
    trough_idx <- which.min(stationary_df$posz)

    peak_posz   <- stationary_df$posz[peak_idx]
    peak_time   <- stationary_df$time_sec[peak_idx]

    trough_posz <- stationary_df$posz[trough_idx]
    trough_time <- stationary_df$time_sec[trough_idx]

    #-----------------------------------
    # 5. Displacement & time
    #-----------------------------------
    approach_disp  <- peak_posz   - baseline_posz
    avoidance_disp <- trough_posz - baseline_posz

    time_to_peak   <- peak_time   - baseline_time
    time_to_trough <- trough_time - baseline_time

    #-----------------------------------
    # 6. Velocity (signed, time-based)
    #-----------------------------------
    approach_velocity <- ifelse(
      time_to_peak > 0,
      approach_disp / time_to_peak,
      NA_real_
    )

    avoidance_velocity <- ifelse(
      time_to_trough > 0,
      avoidance_disp / time_to_trough,
      NA_real_
    )

    #-----------------------------------
    # 7. Output (trial-level)
    #-----------------------------------
    tibble(
      pid = first(trial_df$pid),
      trial = first(trial_df$trial),
      expression = first(trial_df$expression),

      baseline_time = baseline_time,
      baseline_posz = baseline_posz,

      approach_velocity  = approach_velocity,
      avoidance_velocity = avoidance_velocity
    )
  }) %>%
  ungroup() %>%
  mutate(source_file = basename(file_path))
}

#------------------------------------------------------------
# 8. Apply to all files
```

```
#------------------------------------------------------------

velocity_data <- map_dfr(file_list, compute_velocity)

#------------------------------------------------------------
# 9. Quality checks (DO NOT SKIP)
#------------------------------------------------------------

summary(velocity_data$approach_velocity)
summary(velocity_data$avoidance_velocity)

velocity_data %>%
  filter(is.infinite(approach_velocity) |
         is.infinite(avoidance_velocity))

#------------------------------------------------------------
# 10. Save
#------------------------------------------------------------

write.csv(
  velocity_data,
  "~/Desktop/Velocity_Final.csv",
  row.names = FALSE
)
```

CHAPTER 6 – VR Pub Data Preprocessing

HRV Data Preprocessing

HRV was derived from interbeat interval (IBI) values recorded during Trial 3 and Trial 4, representing participants' physiological arousal in response to varying social VR contexts.

Processing Pipeline

1. Trial Selection:
    - Trial 3 and Trial 4 were extracted from raw .tsv files.
2. Time Window:
    - Only data between 16 and 76 seconds were included.
    - The first 15 seconds were excluded to remove early artefacts due to sensor stabilization and physiological noise, as supported by Shaffer & Ginsberg (2017).
    - The 60-second window was selected to maintain internal validity across trials, ensuring temporal consistency.

3. Participant Exclusion:
    - Participants 44 and 45 were removed due to corrupted or missing HRV signals for Trial 1.
4. Artefact Filtering:
    - Physiologically implausible HRV values were removed using fixed cutoffs:
        - HRV < 0 ms (invalid)
        - HRV > 180 ms (likely sensor noise)
5. HRV Calculation:
    - The mean HRV was computed for each participant within the cleaned 60s window.

R Code for HRV Data

```
library(dplyr)
library(readr)

# Load one file (for all 52, use map or loop later)
df <- read_tsv("~/Desktop/VR PUB DATA")

# Clean column names
colnames(df) <- tolower(gsub("\\?", "", colnames(df)))

# Filter for Trial 3 and stable HRV segment (16–76s)
df_filtered <- df %>%
  filter(trial == 3,
         time >= 16,
         time <= 76,
         polar_hrv >= 0,
         polar_hrv <= 180)  # Remove artefacts

# Compute mean HRV
mean_hrv_trial3 <- mean(df_filtered$polar_hrv, na.rm = TRUE)
```

Interpersonal Distance (IPD) Data Processing

IPD represents the minimum distance (in meters) between the participant's position and the centre of the table where the virtual agents stood. It is calculated using head position tracking data on the Z-axis (forward–backward) and filtered by head orientation angles to ensure the participant was actually looking at the table.

Calculation Steps:

1. Starting point: 6 meters away from the group table.
2. Cutoff filter: Only included frames where the participant was within 3 meters of the table (closer = more socially engaged).
3. Gaze direction filter: Used only the frames where the participant's head orientation was within 330°–360° or 0°–30°, meaning they were *looking at the table/agents*.
4. Minimum IPD per trial: From these filtered frames, the smallest distance value was taken as the participant's IPD for that trial.

R Code for IPD Data

```
# Load necessary libraries
library(dplyr)
library(readr)

# Read one participant file
df <- read_tsv("~/Desktop/VR PUB DATA/1-continuous.tsv")

# Rename columns if needed for clarity
colnames(df) <- tolower(gsub("\\?", "", colnames(df)))  # remove question
marks etc.

# Filter to only Trial 3 or 4 (optional if file contains multiple trials)
# If each file is for one participant and one trial, skip this
# df <- filter(df, trial == 3)

# Step 1: Calculate distance to table (already assumed as 'distance'
column)
# Step 2: Only keep rows where participant is within 3 meters of the table
df_filtered <- df %>%
  filter(distance <= 3)

# Step 3: Filter based on head orientation (gaze direction)
# Assuming 'oriy' or similar column indicates yaw (horizontal head angle)
df_filtered <- df_filtered %>%
  filter((oriy >= 330 & oriy <= 360) | (oriy >= 0 & oriy <= 30))

# Step 4: Get minimum distance as IPD
min_ipd <- min(df_filtered$distance, na.rm = TRUE)

# Print result
cat("Minimum IPD:", min_ipd, "meters\n")
```