Spatial Language Abilities and Cognition Across the Adult-Lifespan and in Early Alzheimer’s Disease

PhD Thesis

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Abstract

Space constitutes one of the core framing structures of experience in the natural environment. Therefore, communicating spatial information with verbal means, such as locative relations between objects, is vital for numerous everyday activities and constitutes a core part of human linguistic communication. The present project aimed to 1) develop psychometrically sound measures assessing spatial language abilities, including naming static and dynamic spatial relations, memory for route- and survey-based descriptions, and comprehension of descriptions of locative relations under different spatial reference frames; 2) identify the trajectories of these spatial language abilities across the adult-lifespan and contrast them against trajectories of various (non-verbal) visuospatial and (non-spatial) verbal abilities; and 3) investigate spatial language abilities in individuals who are at an early stage of Alzheimer's disease (AD), for the first time. Across a series of studies involving 160 adults aged between 18 and 85, we found comparable age-related declines in spatial language and visuospatial abilities, although their onset and magnitude depended on the type of subability examined. By contrast, verbal abilities remained well-preserved with increasing age. Moreover, performance in spatial language measures was found to discriminate mild AD patients and age-, education-, and gender-matched controls to a very high degree. The results of the present work have several theoretical and practical implications, as they 1) establish the test-retest reliability, and the concurrent, construct and discriminative validity of the newly-developed spatial language measures; 2) reveal a number of divergent and convergent domain-specific cognitive changes across the adult-lifespan; 3) extend the large existing literature on the detrimental (a)typical ageing effects on visuospatial cognition by demonstrating that spatial processing is also compromised when assessed through language; and 4) suggest that language- and perception-based representations of space are underpinned by comparable cognitive operations and supported by overlapping neural networks that are particularly sensitive to ageing effects.

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Declarations

1. The material offered in the present thesis has not been previously submitted towards the award of a degree.
2. Parts of the present work have been communicated to the scientific community in national and international scientific meetings.
3. The length of the thesis is 85,922 words, excluding material in the appendix.
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“The longer I live, the more beautiful life becomes.”

Frank Lloyd Wright

American architect, designer, writer, and educator (1867-1959)

Chapter 1 General objectives and outline

Spatial representations typically derive from direct visual and navigational experience in the physical world, and therefore, one can argue that they are grounded in the systems of perception and action. However, spatial representations can also originate and, importantly, can be *shared* in human communication with the use of symbolic linguistic constructs, such as spatial descriptions. Spatial language, the ability to communicate spatial representations with verbal means, involves demanding operations of transformation of information, in a way that visuospatial information is translated into linguistic formats, and vice versa.

Studying the mapping between spatial language and spatial abilities in typical and atypical ageing offers a novel and unique window into developing hypotheses about the internal representations on which spatial knowledge is based. On the one hand, the verbal-semantic system is typically well preserved across the adult-lifespan, while, on the other hand, visuospatial abilities usually decline with increasing age. In addition, patients at an early or even prodromal stage of Alzheimer's disease (AD) experience substantial difficulties in spatially orienting in the natural environment. At the same time, AD patients are not aphasic, although their lexical-semantic network may be partially compromised. Therefore, the central question arising in the present studies is whether individuals who experience impairments in visuospatial abilities remain capable of efficient spatial language processing. The answer to this core question is of great theoretical importance: if spatial language abilities are intact despite impaired visuospatial abilities, then that dissociation would suggest a dual mode of cognitive processing of space, with linguistic and visuoperceptual representations of space being independent of each other. If, on the contrary, both linguistic and non-linguistic abilities of processing spatial information are simultaneously affected by (a)typical ageing, one could argue in favour of a supramodal cognitive system supporting spatial representations.

Generating, apprehending, and remembering spatial information based on verbal descriptions is a core part of human communication and essential for managing numerous daily activities. Despite its importance, however, there are surprisingly few studies on how these processes may change in typical and atypical ageing. The main objective of the present project is to thoroughly investigate different aspects of spatial language processing, including, spatial-verbal production, comprehension, and memory, across the adult lifespan and in mild AD. Results will provide fresh insights on the mapping between linguistic and non-linguistic representations of space from an ageing perspective. Moreover, results will help us identify possible impairments in different aspects of spatial language processing in typical and pathological ageing. This, in turn, may lead to the identification of markers of typical and atypical ageing that could be used in clinical settings for earlier and more accurate diagnosis and staging of AD and optimum early intervention designs. Finally, the present studies will establish the reliability and validity of novel measures tapping spatial language for clinical and experimental use.

The current work develops in three main parts, and each part is consisting of a literature review chapter and a chapter presenting novel experimental findings. Part I focuses on spatial language, Part II on typical ageing, and Part III on AD. Within Part I, Chapter 2 provides a literature review on spatial semantics and their relation to non-linguistic spatial cognition, a brief overview of spatial reference frames, and the developmental trajectories of spatial language acquisition from studies with children from different cultural backgrounds. Chapter 3 presents the development of novel measures designed to assess various spatial language abilities, focusing on spatial-verbal production, memory, and comprehension. Within Part II, Chapter 4 focuses on ageing and includes a comprehensive review of the current models of cognitive ageing, as well as the differential ageing effects on language and visuospatial abilities. Chapter 5 presents novel findings regarding the trajectories of spatial language abilities across the adult-lifespan contrasted against a variety of (non-spatial) verbal and (non-verbal) visuospatial abilities. Within Part III, Chapter 6 discusses the main characteristics of AD, and Chapter 7 presents novel results focusing on spatial language deficits in early AD. Finally, Chapter 8 offers a synopsis of the main findings of the present studies along with their theoretical and practical implications, and provides some suggestions for future research directions.

Part I

Spatial language

Chapter 2 Introduction to spatial language

2.1 Spatial semantics (and spatial cognition)

Imagine that you and your family are at home and plan to watch Sir David Attenborough's Planet Earth II on the television, but you realise that your glasses are lost somewhere in the house. Luckily, a member of your family tells you that *the glasses are under the newspaper on the kitchen table*, saving you time from searching for them in every possible location, and thus not having to miss the beginning of the documentary. In order to efficiently manage numerous activities in daily life, people need to communicate information about spatial relations amongst objects in the environment in an effective way. This ability entails the selection of appropriate spatial terms, typically spatial prepositions. Spatial language involves linguistic representations of the geometric and functional properties of spatial relations (Coventry & Garrod, 2005; Landau & Jackendoff, 1993), forming a unique natural linkage between linguistic and perceptual representations.

Spatial prepositions (e.g., *in*, *above*, *in front of*, *towards*, etc.; Table 1) are the primary means of communicating spatial relations (Herskovits, 1997; Landau & Jackendoff, 1993). Therefore, we can assess one's ability to express spatial locations by their use of spatial prepositions. Spatial prepositions are primarily used to denote locations or sequences (changes) of locations, respectively, and therefore, may have concrete locative and/or directional meanings (Zwarts, 1997; 2005). Static locational meanings are usually expressed with an existential verb, such as *be*, while spatial prepositions used for dynamic directional meanings are typically accompanied with a motion verb, such as *go*. Simple locative prepositions involve the use of a single prepositional phrase along with two noun phrases. For example, *the cat is on the mat* describes where the cat (the located object) is positioned with reference to the mat (the reference object). Similarly, *the cat went into the house*, describes the change of location of the cat (the located object) with reference to the house (the reference object). Of course, spatial relations may also be described with more than one prepositional phrase, as in *the bicycle park is in front and to the right of the library*. Some of the spatial prepositions, such as *around*, *in*, *near*, and *on*, only refer to topological relations between objects (Coventry & Garrod, 2004). Others, the so-called projective spatial prepositions, such as *above*, *behind*, *to the left of*, and *right of*, also convey information about the intrinsic or extrinsic direction / orientation in which the located object is positioned with respect to the reference object (Coventry & Garrod, 2004) and may be used within different spatial reference frames (see Section 2.2).

Table 1. *The Prepositions in English*

Spatial prepositions			
		Compound prepositions	Intransitive prepositions
About	From	Adjacent to	Apart
Above	In (inside)	Close to	Away (from)
Across	Into	Far from	Back (Backward)
After	Near (Nearby)	In back of	Downward
Against	Off	In between	East
Along (Alongside)	On (Onto)	In front of	Forward
Amid(st)	Opposite	In line with	Here
Among(st)	Out (Outside)	Next to	Inward(s)
Around	Over	On top of	Left
At	Past	Parallel to	North
Behind	Through	To the left of	Outward(s)
Below	To (Toward(s))	To the right of	Right
Beneath	Under (Underneath)	To the side of	South
Beside	Up		There
Between	Upon		Together
Beyond	Via		Upward(s)
By	With (Within;		West
Down	Without)		

Note. Adapted from Landau & Jackendoff (1993).

It has been argued that only the gross geometric relations between the located and the reference objects are typically represented during verbal encoding of spatial relations with spatial prepositions (the "*where*" system), whereas more detailed geometric properties, such as fine distinctions of shape, are used in order to identify and name objects (with nouns; the "*what*" system) (Landau & Jackendoff, 1993). Accordingly, it can be argued that the "*where*" system represents objects mainly as place markers within coarse geometric constructs, such as *interior*, *outline*, or *contiguous* (Herskovits, 1986).

It is quite obvious that these gross geometric properties must dominate spatial descriptions between abstract objects (e.g., *The triangle is above the circle*). On the other hand, there is accumulating evidence to show that extra-geometric properties of objects with rich situational knowledge are also represented during linguistic processing of spatial relations (Carlson-Radvansky & Radvansky, 1996; Coventry, 1998; Coventry, Carmichael, &

Garrod, 1994; Coventry et al., 2010; Coventry & Prat-Sala, 2001; Coventry, Prat-Sala, & Richards, 2001; Garrod, Ferrier, & Campbell, 1999; for reviews, see Coventry & Garrod, 2004, 2005; Landau, 2016). According to the functional geometric framework proposed by Coventry and Garrod (2004), apart from geometric properties, i.e., *where* objects are located, prior situational knowledge regarding the functionality of objects, i.e., *what* objects are typically for, as well as the functional relations between objects, i.e., *how* objects are typically interacting with each other in a situation-specific context, can also influence the use of spatial prepositions. These extra-geometric variables may involve different kinds of functional properties associated with object knowledge, such as the protective function of an umbrella. For example, Coventry and colleagues (2001, 2010) asked participants to rate the appropriateness of using the spatial prepositions *over*, *under*, *above*, and *below* in descriptions of pictures showing a person holding objects with the function of protection, such as an umbrella or a shield, while manipulating geometrical (i.e., the rotation of the object held) or functional (i.e., the extent to which the objects were fulfilling their protective function) properties of the scene. They found that language ratings for spatial relations were affected by both the geometric and functional manipulations, supporting the notion that both geometrical features and functional qualities of objects underpin spatial semantic processing. Similar extra-geometric effects have also been found for other spatial prepositions, such as *in* and *on* (Coventry et al., 1994; Coventry & Prat-Sala, 2001; Garrod et al., 1999), and *in front of* and *behind* (Carlson-Radvansky & Radvansky, 1996).

Spatial prepositions form a unique semantic class of words, as their use is determined by grounded word-environment relations while it may be influenced by distributional word-word relations. The nature of semantic representations and the extent to which such representations are separate from, versus grounded in, non-linguistic processes has been a major subject in cognitive science and is under debate. According to distributional models, the meaning of a word is based on how it is used within a language (Landauer & Dumais, 1997; Griffiths, Steyvers, & Tenenbaum, 2007). Alternatively, grounded approaches propose that semantic representations are acquired through experiencing and acting in the physical world (Barsalou, 1999; Zwaan, 2004).

It has been noted that grounded approaches to semantic representation might be more applicable to concrete terms referring to the physical world (e.g., *tree*), whereas distributional models might better describe more abstract representations (e.g., *freedom*) (Andrews et al., 2009). Taking into account the environmental context in which language is used, the pluralistic view proposed by Zwaan (2014) argues that the activation of abstract or grounded representations during language comprehension is subject to the level of its environmental embeddedness. In other words, the more the referential situation of a narrative maps onto the in progress communicative situation, the greater activation of embodied representations would be expected, and vice versa. Imagine, for example, a dance instructor explicitly describing the definite steps of a complex dance move whilst actually physically performing the dance move, a context in which perceptual-motor processes must dominate over abstract conceptualization, versus a philosophy lecturer describing to university students the steps of deductive reasoning based on Aristotelian syllogism, a context in which the recruitment of abstract symbols is arguably essential for successful communication.

So semantic processing may employ different mental representations acquired either from the concrete perception and action systems or from arbitrary abstract concepts, depending on the semantic category in which a lexical term belongs as well as on the embeddedness of the environmental context in which the verbal communication unfolds. Spatial language constitutes a natural bridge between the semantic and the perceptual world. Therefore, our ability to express spatial relations through language has to be closely connected to (non-verbal) spatial representations. In fact, it can be argued that spatial abilities are a prerequisite for the linguistic conceptualization and communication of spatial information and relations, as Spence and Feng (2010) proposed.

Several studies have investigated the relation between spatial semantics and spatial representations. Evidence across behavioural (e.g., Coventry, Griffiths, & Hamilton, 2014; Hayward & Tarr, 1995), cross-linguistic (e.g., Munnich, Landau, & Dosher, 2001), and neuroimaging (e.g., Wallentin, Østergaard, Lund, Østergaard, & Roepstorff, 2005) investigations has revealed a strong connection between linguistic and non-linguistic representations of space. For example, Coventry and colleagues (2014) showed in a series of experiments that the use of spatial demonstratives to describe object location and (non-linguistic) memory for object location are governed by the same factors, such as distance, ownership, visibility, and familiarity, suggesting that linguistic representations for space mirror nonverbal perceptual spatial representations. Similarly, cross-linguistic studies have reported that both talking about and remembering locations are strongly influenced by the same kinds of spatial properties, such as the axial structure of a reference object (Munnich et al., 2001).

While there has been a plethora of studies focusing on the neural correlates of (non-verbal) spatial representations, spatial language has received less attention. Naming static spatial relations between concrete objects has been linked with left parietal activation, while right parietal activity has been observed during lexical retrieval for static spatial relations between more abstract entities (Damasio et al., 2001). Recent neuropsychological findings suggest that damage in frontal or parietotemporal regions of the left hemisphere is related to impaired retrieval of words describing static or dynamic spatial relations between concrete objects (Göksun, Lehet, Malykhina, & Chatterjee, 2013). Damage in the inferior frontal cortex has been associated with impaired judgement of spatial descriptions (Amorapanth, Widick, & Chatterjee, 2010). Another study with patients with unilateral brain damage suggested that the linguistic mapping onto static spatial relations is mainly supported by frontal and parietotemporal areas of the left hemisphere whereas the right hemisphere has a key role in nonverbal schematic representation of space (Amorapanth et al., 2012).

Moreover, neuroimaging findings have shown that the processing of sentences that include spatial information is associated with increased bilateral activation in brain regions involved in non-linguistic spatial processing, such as parahippocampal areas and the temporal-occipital-parietal junction (Wallentin et al., 2005), implying a neural overlap between abstract and perceptual representations of space. It has been suggested that the superior parietal lobule underpins the integration of linguistic and spatial information during sentence processing for descriptions of spatial relations between objects (Conder et al., 2017). Furthermore, in an fMRI study employing a matching task of static left/right spatial relations presented in pictures or in sentences, comparisons of spatial prepositions with either visual or verbal descriptions yielded increased activity in the left inferior parietal lobe, suggesting a flexible representation of space in both linguistic and non-linguistic visuospatial modalities (Noordzij, Neggers, Ramsey, & Postma, 2008). Despite differences in the neural and mental organization of linguistic and perceptual representations of space, these two domains seem to be supported by similar neural networks (Chatterjee, 2001). In fact, it has been argued that a supramodal representation of spatial information within a fronto-parietal network of brain regions may enable flexible comparisons and use of spatial information within the verbal and perceptual domain (Struiksma, Noordzij, & Postma, 2009; Struiksma & Postma, 2017).

A few studies examined spatial language production (Landau & Hoffman, 2005; Landau & Zukowski, 2003) and comprehension (Phillips, Jarrold, Baddeley, Grant, & Karmiloff-Smith, 2004) in individuals with Williams syndrome, a rare congenital neurodevelopmental disorder characterized by severe deficits in spatial cognition with relatively unimpaired language abilities. Using the Test of Reception of Grammar (Bishop, 1983), Phillips et al. (2004) found individuals with Williams syndrome exhibiting poor understanding of sentences containing spatial prepositions (e.g., *The bird is below the flower*) but spared comprehension of non-spatial sentences, even with complex grammatical structures (e.g., *Not only the square but also the circle is yellow*). Landau and Zukowski (2003) asked individuals with Williams syndrome to describe 80 simple videotaped motion events, 40 of which involved one object moving in relation to another. They found that these individuals named the objects involved in the videos (e.g., *bottle, box*) and described the manner of motion by using an appropriate motion verb (e.g., *fall, jump, fly*) comparably to matched controls, however, they produced significantly fewer correct terms describing path (e.g., *across*, *through*). Similarly, Landau and Hoffman (2005) reported that children with Williams syndrome perform poorer than controls in non-linguistic judgements of object locations as well as in naming those locations. The results of these studies indicate that non-linguistic spatial representations and spatial language are closely connected, as it is highly likely that the difficulties in certain aspects of spatial language among individuals with Williams syndrome may be affected by the deficits in visuospatial processing. By contrast, some lesion studies have indicated a double dissociation between spatial language and spatial abilities (Tranel & Kemmerer, 2004), supporting Kemmerer and Tranel's (2000) contention that the meanings of spatial words are language-specific semantic structures independent from non-linguistic perceptual representation, and suggesting that these two types of representation are more distantly related.

While existing data seem to support both symbolic and grounded theories of meaning, seldom have these competing approaches been considered simultaneously within the same experimental paradigms. Theoretically there has been a move towards an integrative view in which language processing involves both symbolic and embodied representations (Andrews, Vigliocco, & Vinson, 2009; Lynott & Connell, 2010; Pulvermüller, 2012). For example, Andrews et al. (2009) have shown that experiential and distributional data together more closely map onto human measures of semantic representation than either data set alone, and Lynott and Connell (2010) similarly apply both linguistic distributional information and situated simulations to account for conceptual combination. One might argue that the functional geometric framework for spatial semantic processing (Coventry & Garrod, 2004) is consistent with these hybrid integration accounts. As previously mentioned, apart from the significance of the *geometry* for spatial semantic processing, this theoretical framework acknowledges the influence of prior experiential knowledge of situations in which the objects are linked to (labelled as "*dynamic / kinematic routines*"), as well as the influence of *conceptual knowledge* about objects and their functional properties. By default, geometrical properties are directly accessed through our perceptual systems, and dynamic / kinematic routines are also grounded in the perception and action systems through past situational experience. However, conceptual knowledge can arguably be linked to both grounded and distributional representations. Since spatial language forms a unique word class, lying between the perceptual and linguistic world, more investigations are required that consider simultaneously the relation between spatial language processing with both verbal and visuospatial abilities.

2.2 Spatial frames of reference

Spatial language is a domain that requires coordination between perceptual and linguistic processes, as the perceptual input about spatial relations in the world and the words describing those spatial relations must be mapped onto some mental representation of space (Carlson-Radvansky & Irwin, 1993). These mental representations may employ different reference frames (Burgess, 2006; Carlson, 1999; Levinson, 1996, 2003). A frame of reference is a coordinate "axial" system used to describe the location of objects. Three distinct classes of spatial reference frames have been identified for representing spatial relations between objects in the environment, each based on a different source of information, including the orientation of the viewer/speaker (relative reference frame), the orientation/direction of the reference object in the scene (intrinsic reference frame), or salient environmental features such as the gravitational plane (absolute reference frame) (Carlson, 1999; Levinson, 1996, 2003; Miller & Johnson-Laird, 1976).

Consider, for example, the different ways of describing the spatial relations between the objects illustrated in Figure 1. In the relative (person-centred) frame, spatial relations between physical entities are described with respect to the viewer' point of view in the scene, such that one axis is aligned with the viewer's front and back, another axis is aligned with the viewer's left and right sides, and the other axis with the viewer's upper (head) and lower (feet) ends. Therefore spatial relations in a person-centred spatial representation are determined by the changing position of the viewer/speaker. For instance, by adopting a relative reference frame to mentally represent the scene illustrated in Figure 1, the description *The ball is to the right of the bicycle* means that the ball (the located object) is located right in the visual field of the viewer relative to the bicycle (the reference object). In the intrinsic (object-centred) frame, spatial relations are described with respect to the axes of the reference object (based on the predefined intrinsic sides of the object, i.e., top, bottom, front, back, left, and right) and are consequently determined by the changing orientation of the reference object. For example, *The ball is in front of the bicycle* within an intrinsic reference frame suggests that the ball (the located object) is aligned with the front part of the bicycle (the reference object) (Figure 1). Finally, in the absolute (environment-centred) frame of reference, spatial relations are described with respect to a fixed environmental point, such as the gravitational plane, as in *The house is above the ground* (even if the viewer was standing upside down), or an absolute cardinal direction, as in *The bicycle is south of the house* or *The bicycle is east of the woman* (Figure 1). Mental representations of spatial relations within the absolute reference frame are therefore independent from the changing perspective of the viewer/speaker as well as from the changing orientation of the reference object.

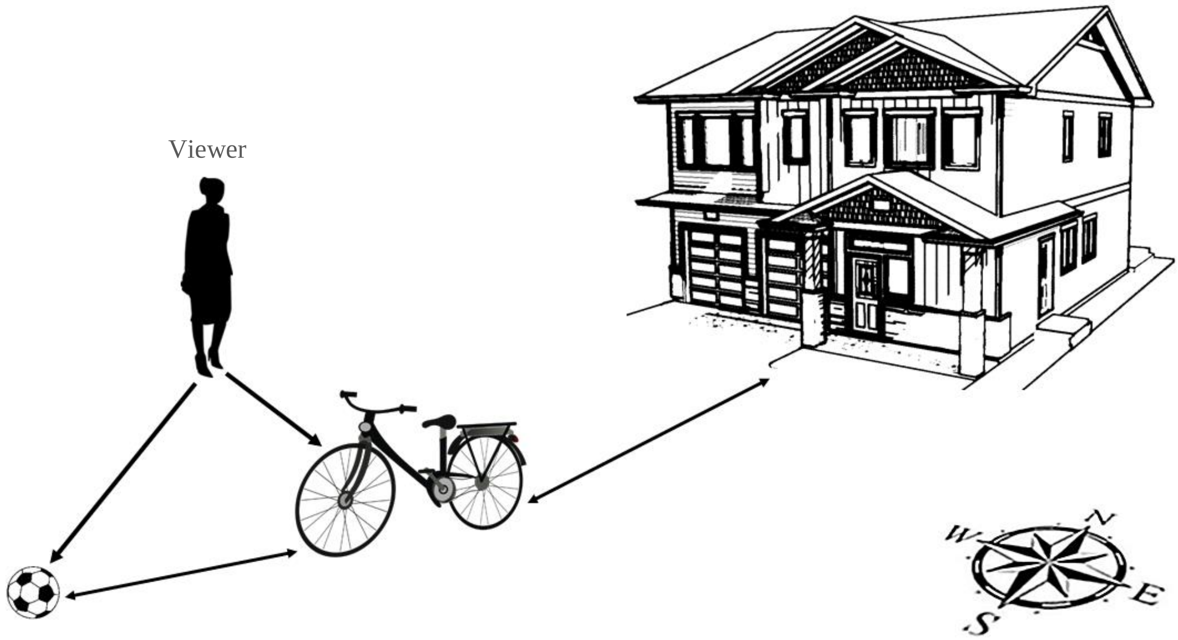


Figure 1. Spatial frames of reference.
Spatial relations can be described within different coordinate reference frames. *The ball is to the right of the bicycle* in the relative reference frame means that the located object is positioned right in the visual field of the viewer relative to the reference object. In contrast, in the intrinsic (object-centred) allocentric reference frame, *the ball is in front of the bicycle* means that the located object is aligned with the front part of the reference object, independently from the viewer's perspective. In the absolute (environment-centred) allocentric frame of reference, spatial relations are independent from the viewer's perspective and from the orientation of the reference object, since they are represented with respect to a fixed environmental point, as in *the bicycle is east of the woman and south of the house*.

Carlson-Radvansky and Irwin (1993; 1994) have shown that there is simultaneous activation of multiple reference frames during descriptions of spatial relations with the spatial terms *above* and *below*. In fact, it has been proposed that this simultaneous activation occurs automatically by constructing a composite spatial template which includes representations from all possible coordinate systems (Carlson-Radvansky & Logan, 1997). Nevertheless, evidence suggests that there are baseline preferences for using a particular reference frame to define spatial relations (Carlson-Radvansky & Irwin, 1993; Carlson-Radvansky & Logan, 1997). The selection of a reference frame is accompanied by inhibition of the non-selected reference frames (Carlson-Radvansky & Jiang, 1998; Carlson & Van Deman, 2008). It has been suggested that reference frame selection is determined by weighting how well the target spatial relation fits into each coordinate axial system (Carlson, 1999) based on a set different parameters, such as the axial system's *orientation* and *direction* (i.e., the axes of a reference frame along the vertical and horizontal dimensions), its' *origin* (i.e., the reference object), and the *scale* or *distance* between the objects that are spatially related (e.g., Carlson & Van Deman, 2004; also see Logan & Sadler, 1996). Salient visual features may influence the reference frame selection, for example, the presence of a horizon in a visual scene may encourage the dominance of an environment-centred reference frame for vertical axis alignment and spatial term assignment (Carlson-Radvansky & Irwin, 1993).

It can be assumed that within a social context, for example in dialogue, individuals need to adopt a common spatial reference frame in order to effectively communicate spatial information. Several studies have shown that people spontaneously adopt the perspective of their social partner while describing or processing spatial relations between two objects (Schober, 1993; Tversky & Hard, 2009), despite the greater processing costs associated with taking another's perspective (Duran, Dale, & Kreuz, 2011). This flexible mental switch in spatial perspective (from a self-centred to a third-person-centred) enables the two interlocutors' mental representations of space to be aligned, and ultimately ensures optimum communication attainment.

Besides language, there has been an enormous amount of research examining frames of reference in perception, attention, memory, and navigation, either from a behavioural or from a neural standpoint (e.g., Marchette, Vass, Ryan, & Epstein, 2014; Mou & McNamara, 2002; Nardini, Burgess, Brecknridge, & Atkinson, 2006; Shelton & McNamara, 2001). Spatial mental representations have also been classified as egocentric or allocentric (Burgess, 2006; Klatzky, 1998; Kosslyn, 1994; Wang, 2012). Subsequently, the relative frame has also been labelled as egocentric, reflecting its dependence on the particular perceptual perspective (viewpoint) of the viewer/speaker. In contrast, the intrinsic and absolute coordinate frames can also be called allocentric, denoting that spatial relations within these reference frames are invariant to the viewer/speaker's perspective or body position and orientation. Although it is highly likely that egocentric and allocentric representations are closely interacting in order to support effective spatial behaviour (for a relevant review of studies with rodents, see Nitz, 2009), there is abundant evidence from both neuropsychological (e.g., Hartley et al., 2007; Medina et al., 2007) and neuroimaging (e.g., Marchette et al., 2014) studies indicating a neural dissociation between the two spatial representation systems, with posterior regions of the hippocampal formation being generally believed to support allocentric spatial representations while the posterior parietal cortex is thought to be more involved in egocentric spatial representations (for reviews, see Burgess, 2006; Galati, Pelle, Berthoz, & Committeri, 2010). Some researchers have argued that allocentric spatial processing is inherently more demanding than egocentric processing (Klatzky, 1998). This is based on the assumption that the self-centred coordinate system can be accessed directly through the perceptual systems without any coordination processes, whereas the externally-grounded nature of allocentric processing requires complex integration processes of spatial relations.

From a developmental standpoint, evidence suggests a progressive acquisition of allocentric spatial processing abilities with age. Several studies have shown that the ability to encode allocentric representations of an environment is present by 2 to 3 years of age (Nardini, Burgess, Breckenridge, & Atkinson, 2006; Ribordy, Jabes, Lavenex, & Lavenex, 2013). However, developmental studies examining the spontaneous and imposed use of egocentric and allocentric strategies during navigation tasks in virtual mazes indicate that the use of allocentric strategies is not fully developed until the age of 10 (Bullens, Iglói, Berthoz, Postma, & Rondi-Reig, 2010). This gradual acquisition of the ability to use allocentric representations might be related to the later maturation of the hippocampus. Posterior hippocampus, which supports spatial learning and memory, gradually increases in volume from early childhood to early adulthood (Gogtay et al., 2006), with the peak of hippocampal volume taking place at preadolescence, at 9-11 years of age (Lin et al., 2013; Uematsu et al., 2012). Integrating egocentric and allocentric representations (Belmonti, Cioni, & Berthoz, 2014; Vasilyeva & Lourenco, 2012) and binding different types of spatial information, such as landmark and route knowledge (Nys, Gyselinck, Orriols, & Hickmann, 2014) matures gradually from childhood to adulthood, perhaps reflecting the gradual development of higher-order cognitive control operations and the gradual maturation of frontal regions in the brain that support them (Purser et al., 2012; Vasilyeva & Lourenco, 2012).

2.3 Developmental trajectories of spatial language acquisition

Understanding the development of spatial concepts in relation to the acquisition of specific linguistic concepts used to denote locational relations may provide valuable insight into the mapping between spatial cognition and spatial language. Over the last few decades, a debate has risen regarding the relationship between spatial cognition and spatial semantics while developing spatial concepts. Traditionally, developmental psychologists claimed that the development of spatial concepts relies on non-linguistic perceptual and cognitive abilities independently from language use, enabling thereafter the development of semantic constructs (for example, see Slobin, 1985). More recent trends, however, suggest that spatial language facilitates the formation of spatial categories (for reviews, see Bowerman & Choi, 2003; Casasola, 2008).

It has been suggested that words such as *in* and *on* represent primitive topological concepts, such as containment (enclosure) and contact or support. The early spatial concepts of containment, contact, and verticality become available in the course of non-linguistic cognitive development in a universal (cross-cultural and cross-linguistic) way. Children initially map the spatial words of their language directly to these basic spatial concepts of simple topological relationships, such as *in* and *out* for containment, *on* for contiguity and support, and *up* and *down* for verticality. Spatial words used to denote more complex spatial concepts, such as proximity (e.g., *near*, *far*, *next to*, *between*, *beside*) are acquired later in development (Bowerman & Choi, 2001; 2003). Projective prepositional phrases, such as *in front of*, *behind*, *left of*, *right of*, *below*, *above*, are acquired even later in development (Bowerman & Choi, 2001; Choi & Bowerman, 1991; Craton, Elicker, Plumert, & Pick, 1990; Johnston & Slobin, 1979), as they involve additional spatial coordination processes with respect to the orientation, and therefore may require the employment of different viewpoints (spatial reference frames; see Section 2.2). In fact, projective terms such as *in front of* and *behind*, are initially used by children for objects in front of or behind their own body, while later they are extended to reference objects with inherent fronts and backs (e.g., *behind the car*), suggesting that children's use of spatial semantics relies on their own spatial concepts. This developmental trajectory is consistent with the sequence of emergence of spatial concepts proposed by Piaget and Inhelder back in the 50s (Piaget & Inhelder, 1956), leading to the putative hypothesis that non-linguistic cognitive development sets the pace in spatial semantics development.

Furthermore, evidence from studies with English-speaking children and adults (Lakusta & Landau, 2005; 2012) as well as from cross-linguistic studies with children and adults (Regier & Zheng, 2007), suggest that there is a robust bias for goal paths (e.g., *into the house*) in preference to source paths (e.g., *out of the house*) during verbal descriptions of dynamic spatial relations in motion events. Lakusta and colleagues (2007) found that pre-linguistic infants exhibit a homologous attentional preference for goal objects over source objects during motion events. Based on these findings, it can be argued that the asymmetric way of representing dynamic spatial relations emerges very early in development and is later mapped into language. Moreover, Balcomb, Newcombe, and Ferrara (2011) reported a positive correlation between place learning (using an adapted Morris water maze task) and use of spatial prepositions in children aged between 16 to 24 months, indicating a close relation between the emergence of linguistic skills and non-linguistic skills that rely on shared representations of space. However, they also found that several children who succeeded in place learning did not use prepositions in an effective way, suggesting that non-linguistic spatial understanding precedes spatial language acquisition.

The evidence described above are in line with the notion expressed years ago by Johnston and Slobin (1979) that as new spatial representations mature, linguistic terms emerge to express them. It has been shown for example, that the quality of verbal information in children's descriptions of a route varies mostly with their visuospatial abilities and not with their verbal abilities (Nys et al., 2014). On the other hand, evidence of language-specific variation in early acquisition of spatial semantics as reported in cross-linguistic studies, suggest that toddlers learning different languages classify spatial relations in different ways (and in different coordinate systems) based on their corresponding linguistic environment (Bowerman & Choi, 2001; 2003; Choi & Bowerman, 1991; Choi, McDonough, Bowerman, & Mandler, 1999), and that the acquisition of spatial semantics influences infants' early categorization of spatial relations (Bowerman & Choi, 2001). For example, in some Asian cultures (e.g., in Bali, Indonesia, and in certain areas of India and Nepal) children and teenagers tend to use an absolute (environment-centred) coordinate system during spatial encoding, similarly to how reference to spatial locations is organized in their linguistic environment (Mishra, Dasen, & Niraula, 2003; Wassmann & Dasen, 1998). By contrast, Western cultures typically favour the use of an egocentric reference frame in language, which is also reflected in non-linguistic spatial representations. These results have led a lot of researchers to support the classical Whorfian hypothesis that language shapes cognition (see Majid, Bowerman, Kita, Haun, & Levinson, 2004).

Some researchers have proposed that language may affect children's spatial cognition, insofar as exposing them to linguistic categorization of space can draw their attention to spatial categorical distinctions and conceptual representations that would otherwise go unnoticed (e.g., Bowerman & Choi, 2001). One of the most well-known examples is the difference between English and Korean (Choi & Bowerman, 1991). English speakers linguistically express relations of containment with the preposition *in* while relations of support are expressed with the preposition *on*. In contrast, Korean speakers linguistically organize spatial relations of both containment and support in a single semantic category but differentiate spatial relations based on whether the two objects *fit* with one another: they use the term "kkita" to express tight-fit relations, and a separate term, "nehta" to express loose-fit relations. There is evidence to suggest that this cross-linguistic difference leads toddlers to organize the same spatial events into different semantic categories (Choi et al., 1999), and is also reflected in adults' non-linguistic spatial representation of the dimension *fit* (McDonough, Choi, & Mandler, 2003).

It has been found that a familiar spatial word (e.g., *on*) can facilitate infants' ability to form an abstract categorical representation of spatial relations (e.g., the concept of support) (Casasola, 2005). Moreover, Pruden, Levine, and Huttenlocher (2011) reported that toddlers' production of spatial terms can predict their performance on non-linguistic spatial tasks. In line with these spatial language effects on non-linguistic spatial cognition, a recent study revealed that deaf children who have not been exposed to a spoken or sign language, and consequently lacked linguistic encoding of spatial relations, perform worse than children who have learned conventional terms for spatial relations on non-linguistic spatial mapping and spatial memory tasks (Gentner et al., 2013), suggesting that holding linguistic resources for encoding spatial relations may be beneficial for non-linguistic spatial processing.

As discussed earlier, geometric properties as well as specific knowledge of objects and their typical functional relationships may influence the use of spatial prepositions (Coventry & Garrod, 2004). Landau (2016) recently proposed that spatial prepositions for geometry-based spatial relations are acquired during a relatively short timeline, especially if no shifting to another reference frame is required, and show little cross-linguistic variability. By contrast, using spatial prepositions for relationships that are co-defined by functional properties might be subject to considerable cross-linguistic variability and constitutes a skill that is fully mastered after longer periods of time.

2.4 Conclusions

Our ability to use words to refer to physical entities and relationships is vital for managing everyday activities and constitutes a core part of human linguistic communication. Spatial language involves linguistic representations of spatial relations, which are defined by geometric and functional properties (Coventry & Garrod, 2004; Landau, 2016; Landau & Jackendoff, 1993), and its primary means are spatial prepositions. It forms a natural bridge between language and perception as it requires effective coordination between perceptual and linguistic processes onto some mental representation of space (Carlson-Radvansky & Irwin, 1993). These mental representations may employ different spatial reference frames (RF) that can be person-centred (relative RF), object-centred (intrinsic RF), or environment-centred (absolute RF) (Carlson, 1999; Levinson, 1996, 2003).

From the background provided in this chapter, there is considerable evidence to support that spatial semantics and non-linguistic spatial cognition are closely interconnected (e.g., Chatterjee, 2001; Coventry et al., 2014; Munnich et al., 2001; Noordzij et al., 2008) and that the representational systems share underlying structural similarities (Hayward & Tarr, 1995). A flexible view on the relationship between spatial cognition and spatial semantics during early development would propose that attentional tuning to spatial concepts can be bi-directional, i.e., a child who notices a spatial concept is more likely to notice its label, and vice-versa. According to Casasola (2008), infants recruit any perceptual and cognitive tool that is available to them while forming spatial concepts, and as they eventually build a spatial lexicon, spatial language becomes an additional tool.

Despite the numerous studies investigating the developmental trajectories of spatial semantics in early life, the effects of typical and atypical ageing on spatial language processing are largely unexplored. However, it is of great importance to examine this unique human ability across the whole spectrum of normal cognitive development, from children to older adults. Additionally, investigations examining probable ageing differences in spatial language in comparison to ageing differences in verbal and visuospatial abilities may help us identify how spatial language is related to symbolic representations from the linguistic domain and to grounded representations from the visuospatial domain across the adult lifespan. Furthermore, studies tackling potential deficits in spatial language among neurological patients, such as patients with neurodegenerative disorders, are desperately needed. Understanding profound deficits of spatial thought and language is critical to designing targeted interventions. A greater focus on spatial language and its deficits will deepen our understanding of the communication problems neurological patients might experience that would not be evident by only examining object knowledge.

In order to identify possible changes in our ability to communicate spatial information with verbal means in adults who are ageing typically and atypically, we developed four novel measures particularly designed to assess spatial language processing, and more specifically, spatial verbal fluency, spatial naming, spatial verbal memory, and verbal comprehension in spatial reference frames. The next chapter provides detailed descriptions of each novel spatial language measure along with their administration and scoring procedures, as well as the results of a pilot study with a sample of healthy young adults, and the results of a study examining their test-retest reliability.

Chapter 3 Development of measures assessing spatial language processing (1st series of studies)

3.1 Rationale

Over the last century, the increasing need for reliable and objective measures of cognitive functioning has led to the construction of numerous assessment instruments. Various paper-and-pencil tests have been developed in order to evaluate different cognitive abilities across the verbal and the visuospatial domain. Visuospatial tests typically assess abilities of organizing visuospatial information (e.g., the Hooper Visual Organization Test; Hooper, 1983), mentally manipulating them (e.g., the Mental Rotation task; Shepard & Metzler, 1971), and operating them in a reasonable manner (e.g., the Matrix Reasoning subscale from the Wechsler Adult Intelligence Scale; Wechsler, 2010). Furthermore, several paper-and-pencil tasks have been developed to examine episodic visuospatial memory, such as the Rey-Osterrieth Complex Figure Test (Osterrieth, 1944; also see Strauss, Sherman, O'Spreen, 2006).

Verbal abilities are largely divided into production and comprehension. One of the most common aspects of verbal ability evaluations involves some form of vocabulary assessment or verbal comprehension (e.g., the Wechsler Vocabulary subtests from the Wechsler Adult Intelligence Scale, Wechsler, 2010; the Mill Hill Vocabulary Test, Raven, 1975; etc.), because they offer an easy and unambiguous means of evaluating one's verbal knowledge. Another widely used type of task assessing verbal abilities is confrontation naming (e.g., the Boston Naming Test; Kaplan, Goodglass, & Weintraub, 2001), in which the subject is shown a target picture and then is asked to name it. Performance in naming tasks relies on lexical access, retrieval, and matching to a target item (Zec, Markwell, Burkett, & Karsen, 2005), and is primarily evaluated based on naming accuracy, although naming speed is also frequently recorded (Forster & Chambers, 1973). Verbal fluency tasks are also often included in assessments of executive functioning within the verbal domain (Strauss et al., 2006). In these tasks, the participant is requested to generate as many words of a particular category as possible in a limited period of time (e.g., 60 sec). Typical categories include phonemic cues, (i.e., words beginning from specific letters, such as *F*, *A*, or *S*), and semantic cues (for example, exemplars of *animals*). Performance in fluency tasks is subject to access and retrieval of items from long-term memory, and is typically measured by the total number of different items produced within the specified period of time. Verbal fluency tasks involve effortful lexical-semantic processing and word retrieval components, as in (picture) naming tasks, but in the absence of prompting stimuli (pictures). Moreover, several instruments have been developed for the assessment of verbal memory. Episodic verbal learning and memory is often evaluated by lists of words (e.g., the California Verbal Learning Test; Delin, Kramer, Kaplan, & Ober, 2000) or by assessing recollection memory for short texts (e.g., the Logical Memory subscale of the Wechsler Memory Scale; Wechsler, 2010).

Some important considerations when developing or using cognitive assessment tools in clinical settings is their acceptability and burden on subjects. Repetitive test items can easily lead to boredom even among healthy older adults (e.g., Sano et al., 2013), thus decreasing engagement and motivation to complete the tasks at the best possible way. Moreover, although automated computerized tests have many advantages, such as savings of costs and time, standardized administration and accurate performance recordings, they can appear intimidating and counterintuitive to older adults. Computer-based tests can be particularly challenging for people with visual limitations, or they can be too fast-paced or difficult for people who are unfamiliar with computers, leading to computer anxiety, which can influence their performance as well as their willingness to undergo such testing procedures (Silverberg et al., 2011; Werner & Korczyn, 2012). Furthermore, some of the methods implemented in automated cognitive tests, such as procedural complexity, the inability to ensure that the participant has fully understood task instructions, the inability to temporarily pause tasks if the participant becomes fatigued or distracted, can seriously compromise the quality of the results. On the other hand, social interaction with a clinician promotes motivation and engagement while completing tasks (Motter, Devanand, Doraiswamy, & Sneed, 2016). For all these reasons, clinicians and researchers have been recommended to make cautious and well-informed decisions about the appropriateness of computerized and on-line neuropsychological testing in clinical populations (Gates & Kochan, 2015).

As discussed in Chapter 2, spatial language constitutes a core part of human linguistic communication, as it refers to our ability to use words to denote spatial relations. Despite its importance, there are no standardized tests available for the assessment of spatial language abilities. Many of the past investigations examining spatial semantics within production (naming) or verification tasks, were typically focusing on a limited amount of spatial terms (e.g., *on* and *in*) while manipulating geometric and/or extra-geometric factors in the scene (e.g., Carlson-Radvansky & Radvansky, 1996; Coventry et al., 1994, 2001, 2010, 2014; Garrod et al., 1999; Landau, Johannes, Skordos, & Papagrafou, 2016), or while considering cross-linguistic differences in verbal descriptions of specific configurations, such as tight-fit relations (e.g., Bowerman & Choi, 2001, 2003; Choi & Bowerman, 1991) or containment and support (e.g., Bowerman & Pederson, 1993; Levinson & Wilkins, 2006). Therefore, those tasks were not developed as tools for the assessment of spatial language abilities, but rather as means of eliciting spatial terms within different experimental conditions. Furthermore, some production tasks were constrained in two-dimensional configurations of objects as stimuli, such as the stimuli developed by Hayward and Tarr (1995) and later adapted in other studies (e.g., Landau & Hoffman, 2005), thus excluding some basic spatial relations, such as *in front of* and *behind*. Similarly, the spatial naming task used by Göksun et al. (2013) included photographs and short movie clips depicting only four different spatial relations in the static condition (*in, on, above, below*) and five relations in the dynamic condition (*in, on, over, under, across*), with concrete objects with rich situational knowledge (e.g., *The apple in the bowl*).

In order to fill this gap, we developed four new tasks specifically designed to assess different aspects of spatial language processing, including spatial verbal production (Spatial Naming Test, Spatial Verbal Fluency task), memory (Spatial Verbal Memory task), and comprehension (Verbal Comprehension in Spatial Reference Frames). Apart from developing them in order to cover a broad spectrum of spatial language abilities, the tasks were designed to match existing widely-used neuropsychological tasks, if applicable, in order to allow direct comparisons between spatial language and non-spatial language measures. Another advantage of designing them as analogues of well-established non-spatial verbal measures, lies in the adoption of certain features regarding the stimuli as well as the administration and scoring procedures that facilitate use with clinical populations. The tasks were designed to have a game-like quality, promoting individuals' motivation and engagement in completing them. Moreover, the basic requirements of each task are easy to communicate and are grasped easily by respondents. In addition, they are short enough to be completed by vulnerable groups, such as patients with neurological conditions that may be prone to fatigue, but long enough to be powerful in measuring spatial language abilities.

A critical characteristic of the novel tasks is their focus on geometry-based (and not functionality-based) spatial relationships, that are linguistically expressed by prepositions to denote locations (e.g., *over, below, on, in, left, beside, near, between, opposite, in the middle, North of,* etc.) or sequences of locations (e.g., *at, towards, around, across, through, downwards, into, up, off, to the left,* etc., i.e., spatial prepositions; see Table 1). Terms that describe spatial information other than locational relations, such as adjectives for size (e.g., *small, short, narrow, empty, wide,* etc.), adjectives for distance (e.g., *high*, *deep*, etc.), or adjectives for shape (e.g., *circular, flat,* etc.), as well as words describing the form of enclosed objects (e.g., *sphere, triangle, diamond,* etc.), amounts and units (e.g., *half, a little, a lot, much, a few meters,* etc.), or deictics (*e.g., here, there, somewhere,* etc.), were excluded. Detailed descriptions of each task are provided below.

3.2 Description of the spatial language measures

3.2.1 Spatial Verbal Fluency task

As mentioned earlier, verbal fluency tasks require participants to freely generate as many different words as possible according to specific cues (e.g., phonemic and semantic cues) within a limited period of time (i.e., 60 sec). In semantic verbal fluency tasks, participants are usually asked to generate as many exemplars of animals (nouns) or actions (verbs) as possible, while in phonemic verbal fluency tasks, subjects are asked to generate as many words beginning with a particular letter (*F*, *A*, or *S*) as possible. We developed the Spatial Verbal Fluency (SVF) task in order to evaluate word production for a unique and largely unexamined word class that includes terms describing locative spatial relations (e.g., *on*, *in*, *above*, *in front of*, etc.), in the absence of prompting stimuli (pictures).

Procedure. Instructions for the Spatial Verbal Fluency task are as follows: *I would like you to tell me all the words you can think that people use to describe where things are, words that people use to describe locations. Can you give me an example of a word that we use to describe where things are?* If the response is acceptable, participants are further instructed: *That's the idea. Now I would like you to tell me as many words that are used to describe locations (where things are) as possible, in one minute*. If the subject has difficulty understanding the task, more clarifications are given by providing an example (e.g., something can be *above* something) and by stating that we are looking for all the words that would be an appropriate answer to the question *where*.

As in standard administration procedures of Verbal Fluency tasks (Kosmidis et al, 2004; Strauss et al., 2006), participants are instructed to avoid repetitions and variations of the same word (e.g., *close – closer*). Participants are allowed 60 sec for the trial, during which their responses are recorded verbatim. Participants are not given any guidelines regarding how to organize their word search and production (e.g., relational opposites, like *inside – outside*; alphabetical clusters, like *about – above – across*; semantic clusters, like *next to – beside – adjacent to – by*).

Scoring. Performance is based on the total number of correct responses generated in one minute. Any identical or variations of a previously given word (e.g., *close – closer*) are considered repetition errors. Items irrelevant to the designated category (e.g., *big*) are considered intrusion errors.

3.2.2 Spatial Naming Test

The Spatial Naming Test (SNT) was developed as a brief screening instrument designed to assess naming abilities for static and dynamic spatial relations between objects. It was designed as an analogue of existing picture confrontation naming tests for objects (e.g., the Boston Naming Test, BNT; Kaplan et al., 2001; for a description see Section 5.2.3.4, for sample items see Figure A in the Appendix) and actions (e.g., the Action Naming Test, ANT; Obler & Albert, 1979; for a description see Section 5.2.3.4, for sample items see Figure B in the Appendix). The stimuli of the SNT consisted of line drawings of simple geometrical shapes (Figure 2; see Table A in the Appendix for all items of the SNT), with a red ball as the located object and an open cube as the reference object (or more cubes when necessary, as in cases of *between, in the middle, among*). Black balls were also depicted in order to create a set of different spatial relations, in an attempt to elicit the most suitable response for the target spatial relation in a way that is distinguishable from the non-target relations.

The SNT was designed to tap geometry-based relations, excluding functionality-based relationships between objects (also see Chapter 1). Therefore, geometrical shapes were deliberately chosen instead of everyday concrete objects in order to avoid biased responses based on typical descriptions of commonly encountered spatial relationships (e.g., "the cat is *on* the mat"). Furthermore, the use of abstract geometric objects excludes language-specific merely conventionalized descriptions of spatial relations, as in "the bird is *in* the tree" or "the fly is *on* the ceiling", or the difference between "being *in* the car" versus "being *on* the bus", or "the food *in* the dish" versus "the food *on* the plate", or "sitting *in* the armchair" versus "sitting *on* the sofa", and so on and so forth.

Each target item of the SNT corresponded to a single English spatial preposition or prepositional phrase, although in some cases more than one preposition was appropriate (e.g., *under*, *underneath*, *below*). As mention earlier (Section 2.1), depending on the context, spatial prepositions may have concrete locative and/or directional meanings (Zwarts, 1997; 2005). When used in descriptions of static spatial relations to denote locations, they have a locative meaning (e.g., "The cat is *on* the mat"). In descriptions of dynamic spatial relations they are used to denote paths, i.e., sequences of locations / changes of positions (e.g., “The cat jumped *onto* the table”), having a directional meaning. Consequently, the test was divided into two parts: Part A consisted of 15 pictures containing static spatial relations, requiring the description of locations (see Figure 2, panels A and B); Part B consisted of 15 pictures containing dynamic spatial relations, requiring the description of the change of locations (see Figure 1, panels C and D).

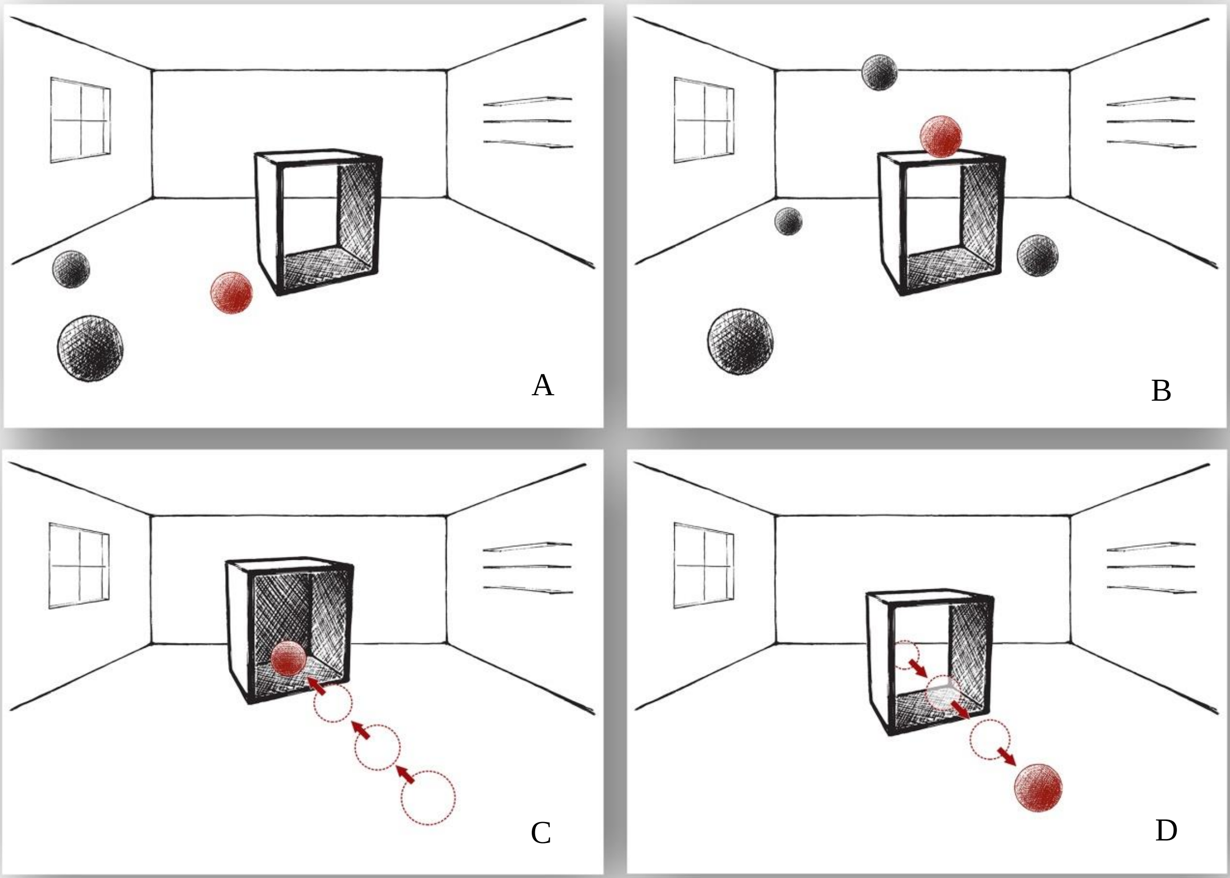


Figure 2. Stimuli samples of the Spatial Naming Test across static (A: *near*; B: *on*) and dynamic (C: *into*; D: *through*) spatial relations.

Procedure. At the outset of each part, participants are given one example trial [one locative (i.e., *The red ball is to the left of the cube*) and one directional (i.e., *The red ball is moving to the left*), not used as test items]. Next, they are shown 30 test items (Table A in the Appendix), one at a time. In each test item, participants are asked to describe as accurately as possible the location (Part A) or the change of location (Part B), respectively, of the located object (red ball) in relation to the reference object (cube) in a way that identifies its location uniquely, distinguishing it from the black balls' location. Respondents are explicitly instructed to base their responses from their viewpoint, and they are encouraged to use spatial prepositions. If necessary, they are instructed to avoid using a clock face system (e.g., *The red ball is at three o'clock*) or compass directions (e.g., *The red ball is North of the cube*). However, there is no constraint on the number of prepositions that they could use to describe the relation. Responses are recorded verbatim.

Scoring. Optimal responses are scored one point (e.g., *into* for the relation depicted in Figure 2C), whereas a less accurate but not incorrect response is scored as a half point (e.g., *towards* for the relation depicted in Figure 2C). Table 2 contains a non-exhaustive list of acceptable responses and their scores. The number of correct responses given in each part is calculated as an index of naming accuracy. There are no time limits in the SNT, but time to complete each part of the test may be recorded optionally as an index of naming speed.

Table 2. *General Scoring of Acceptable Responses in the Spatial Naming Test*

	Score	
Test item	1 point	½ point
Part A – Static spatial relations		
A1	In; inside; within	
A2	(To the) right (of)	
A3	On; on top (of)	
A4	Above; over	Up high from the cube
A5	Behind; back of	
A6	Under; underneath; beneath; below	
A7	Below; under; underneath; beneath	
A8	In front (of)	
A9	Far; far left; furthest left; away; distant left	
A10	Near; near left; nearer; close(r) to	
A11	Next to; beside; alongside; adjacent to; by the side; touching the left side; attached to the left side; adjoining the left side	Near; nearer; nearest close, closer, closest)
A12	Between; in the middle; in the centre	
A13	Among; amongst	
A14	In the middle; in the centre	
A15	Opposite of; in front on the other side	Right in front; in front
Part B – Dynamic spatial relations		
B1	Down; downwards	
B2	Up; upwards	
B3	Right	
B4	Across; right all along	Right
B5	Into; towards inside	Towards; at
B6	Out of; outside of	Away from
B7	Away from; far away	

B8	Around; round; circling	
B9	Over; above	
B10	Under; underneath; beneath; below	
B11	Through	
B12	Onto; on top	Over and up
B13	Down of; off of; away from the top of	From the top of
B14	Along; past; parallel to; across the front; across right to left	Left in front of; right to left of
B15	Towards the side; to the side; next to; beside	Towards; to; at; near

3.2.3 Spatial Verbal Memory

The Spatial Verbal Memory (SVM) task was developed as an analogue of the Logical Memory subscale of the Wechsler Memory Scale (WMS; Wechsler, 2010) in order to assess episodic memory for spatial descriptions presented from two distinct perspectives (route and survey). Spatial descriptions of an environment can typically adopt two different main perspectives (or spatial reference frames): route and survey (Tversky, 1991). Route descriptions are based on the viewpoint of a person who is moving through the environment, where spatial relations are defined with respect to the body axes and orientation of the perceiver, and are therefore subject to the changing perspective/viewpoint of the perceiver. Route descriptions typically have a linear organization, provided by the order in which landmarks appear along the route itself (Tversky, 1991). On the other hand, survey descriptions are based on an extrinsic frame of reference providing an overview of the spatial layout, independent from the viewpoint of the perceiver, and they typically have a hierarchical organization (Taylor & Tversky, 1992).

Consequently, two novel spatial texts were developed, containing spatial descriptions either from a route (i.e., person-centred coordinate system) or a survey (i.e., extrinsic coordinate system) perspective, respectively. Each text was matched in length to the Logical Memory subscale of the WMS (Wechsler, 2010), containing 25 semantic units, 10 of which provided spatial information (Table 3). The route description contained path locations described relative to the dynamic position of an individual within an outdoors natural environment (e.g., *When he saw the Blue Lake in front of him, he turned left*). The route description followed a linear organization, given by the order in which landmarks appeared along the route. The survey description contained locations of buildings within an urban environment, described from a static, external perspective (e.g., *The Library is situated in front of the Church and to the right of the Town Hall*), following a hierarchical organization.

Procedure and scoring. Administration is similar to the guidelines of the WMS manual for the Logical Memory subscale (Wechsler, 2010). Briefly, each text is read once to the participant, who then is asked to orally repeat it immediately and after a ~ 25-minute delay. All free recall units are separately recorded during the immediate and delayed trials, and each correct unit is scored one point. At the outset of the task, participants are instructed to try to remember the stories because they will be asked to repeat them again later. Similarly to the administration guidelines of the Logical Memory subscale, a standard cue is provided in each delayed trial if the participant has no memory of the story (see Table 3).

Table 3. *Items in the Spatial Verbal Memory task*

	Content	Delayed free recall cue
Route description		
	Alex was **on** the main path **at** the Great Mountain, and started walking **towards** the peak. When he saw the blue lake **in front of** him, he turned **left**. He kept the lake **on his right**, until he passed **under** a large oak tree. He then crossed **over** a wooden bridge, leaving the lake **behind** him. He continued walking **straight on** and after a while he reached the peak.	The story was about a man who was walking.
Survey description		
	The Town Hall is **in the centre of** the town. **Around** the Town Hall are a number of buildings. The Library is situated **in front of** the Church and **to the right of** the Town Hall. The Market is just **behind** the Town Hall, **next to** the Museum. The Gardens are **nearby**, located **to the left of** the Town Hall. **On** the main avenue, which runs **along** the Town Hall, there are many pubs and restaurants.	The story was about the Town Hall and the other buildings.

Note. Terms providing spatial information are in bold.

3.2.4 Verbal Comprehension in Spatial Reference Frames

The Verbal Comprehension in Spatial Reference Frames (VCSRF) task was developed in order to assess the ability to process descriptions of locative spatial relations under different spatial reference frames (SRF). Building on previous classification models of SRF (Carlson, 1999; Levinson, 1996; 2003), the VCSRF was designed to include four distinct conditions: (1) a self-centred and (2) a third-person-centred (relative) SRF, (3) an object-centred (intrinsic) SRF, and (4) an environment-centred (absolute) SRF. While in the self-centred

SRF spatial relations are coded egocentrically, relatively to the examinee's viewpoint, performance in the other SRF entails spatial perspective transformations involving self-based mental rotations (Kessler & Thomson, 2010; Kessler & Rutherford, 2010; Zacks, 2008; Zacks & Michelon, 2005). In the third-person-centred SRF, spatial relations are defined relatively to another person's viewpoint, requiring from the examinee to adopt the third-person's perspective. Switching from a self-centred to a third-person-centred perspective may occur in social contexts, for example in dialogue, enabling the two interlocutors' mental representations of space to be aligned, and ultimately ensuring optimum communication attainment. The object-centred SRF involves spatial relations defined by the axial orientation of the reference (ground) object, independently of the viewpoint of the perceivers. Finally, under an environment-centred SRF, spatial relations are described with respect to a fixed point in the external environment, independently of the perceivers' viewpoint or the orientation of the reference object.

Apparatus. The apparatus of this task consisted of a central circular board with a diameter of 18 cm, on which the reference object (a glass or a car miniature in the object-centred condition) is placed, surrounded by a rotating circular board with a diameter of 28 cm, on which the located object (a ball) is permanently placed, based on a third stable circular board with a diameter of 37 cm. The middle board of the apparatus is rotated in order to move the located object into 8 different locations relatively to the reference object, with Location I being directly in front of the participant, and the rest of the locations being equally distributed along the rotating board in a clockwise order (see Figure 3). In the third-person-centred condition, a Lego mini-figure, facing the reference object, is placed directly opposite of the participants' location (Location V; Figure 4). In the environment-centred condition, an arrow pointing to the North is placed ~ 4 metres away at an angle of 45 degrees to the right of the participants' position (Figure 4).

Procedure. In each one of the four conditions, participants hear 16 different statements describing spatial relations between the located and the reference objects (e.g., *The ball is to the left of the glass*), and are asked to judge each statement as true or false. Participants are explicitly given instructions as to which reference frame they should base their judgements on each condition (e.g., in the object-centred condition: *This time, you should base your judgments with reference to the car's perspective*). Each reference frame is explained to participants at the outset of each condition. Figure 4 contains a schematic representation of all four conditions in the VCSRF task, along with the general instructions used for the spatial reference frame employed in each condition and a sample statement describing a spatial relation between the located and the reference objects. Table 4 contains all the items used in the VCSRF task.

Scoring. The total number of correctly judged statements in each condition is calculated as an index of accuracy of performance. There is no time limit in VCSRF, but the time it takes to complete each condition can be measured as an index of speed of performance.

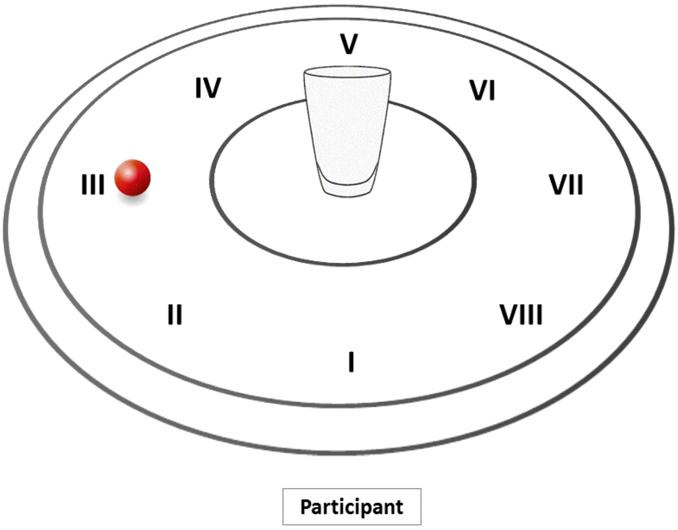


Figure 3. A schematic representation of the apparatus of the Verbal Comprehension in Spatial Reference Frames task. The middle circular board of the apparatus is rotated in order to move the located object (red ball) into 8 different locations relatively to the reference object (glass; car in the object-centred condition). Each Latin number corresponds to one of the possible locations of the located object. Possible locations are not marked on the apparatus in order to eliminate the possibility of being used as facilitating cues by the participants.

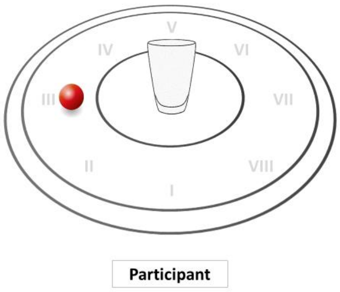
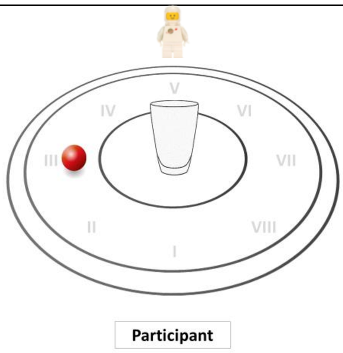
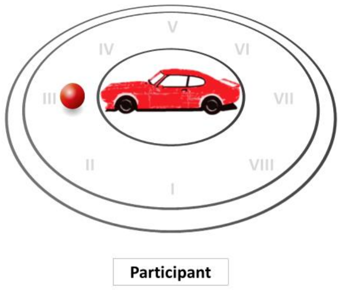
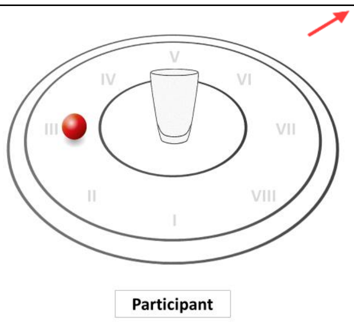
Spatial reference frame	Schematic representation	Instructions	Sample statement
Self-centred		*Based on your perspective*	*The ball is to the left of the glass.* (Correct response: *True*)
Third-person-centred		*Based on the other person's perspective*	*The ball is to the left of the glass.* (Correct response: *False*)
Object-centred		*Based on the car's perspective*	*The ball is to the left of the car.* (Correct response: *False*)
Environment-centred		*Based on the North (as pointed by the arrow)*	*The ball is South-West of the glass.* (Correct response: *True*)

Figure 4. Schematic representation of all conditions in the Verbal Comprehension in Spatial Reference Frames task. The middle board of the apparatus is rotated in order to move the located object (red ball) into 8 different locations relatively to the reference object (glass; car in the object-centred condition). In the third-person-centred condition, a Lego mini-figure, facing the reference object, is placed directly opposite of the participants' location. In the environment-centred reference frame, an arrow pointing to the North is placed ~ 5 metres away at an angle of 45 degrees to the right of the participants' position. The third column presents the general instructions used to describe the spatial relations in each condition. The fourth column provides sample statements describing a spatial relation between the located and the reference object.

Table 4. *Items used in all Conditions of the Verbal Comprehension in Spatial Reference Frames Task*

	Relative RF				**Intrinsic RF**		**Absolute RF**	
	Self-centred		**Third-person-centred**		**Object-centred**		**Environment-centred**	
Item	Loc	Statement (CR)	Loc	Statement (CR)	Loc	Statement (CR)	Loc	Statement (CR)
1	III	To the left of (T)	II	Behind & to the right of (T)	III	In front of (T)	VI	North of (T)
2	VII	To the right of (T)	V	Behind the (F)	VIII	Behind & to the left of (T)	IV	North-West of (F)
3	II	In front & to the left of (T)	VII	To the left of (T)	VI	Behind & to the left of (F)	I	South-East of (T)
4	V	In front of (F)	VIII	In front & to the right of (F)	IV	In front & to the right of (T)	VII	North-East of (T)
5	VIII	In front & to the left of (F)	III	To the left of (F)	VII	To the right of (F)	II	South-West of (F)
6	IV	Behind & to the right of (F)	VI	In front & to the left of (T)	II	In front & to the left of (T)	VIII	East of (T)
7	VI	Behind & to the right of (T)	IV	In front & to the right of (T)	V	To the left (F)	V	North of (F)
8	I	In front of (T)	I	In front of (F)	I	To the left (T)	III	West of (F)
9	V	Behind the (T)	VIII	Behind & to the left of (T)	IV	In front & to the left of (F)	VII	East of (F)
10	II	Behind & to the left of (F)	III	To the right of (T)	VIII	Behind & to the right of (F)	IV	West of (T)
11	VIII	In front & to the right of (T)	V	In front of (T)	III	To the left of (F)	V	North-West of (T)
12	VI	In front & to the right of (F)	II	In front & to the left of (F)	II	In front & to the right of (F)	I	South of (F)
13	III	To the right of (F)	VI	Behind & to the right of (F)	I	In front of (F)	VI	North East of (F)
14	IV	Behind & to the left of (T)	I	Behind the (T)	VI	Behind & to the right of (T)	III	South West of (T)
15	I	Behind the (F)	IV	Behind & to the left of (F)	V	To the right of (T)	VIII	South East of (F)
16	VII	To the left of (F)	VII	To the right of (F)	VII	Behind the (T)	II	South of (F)

Note. RF = reference frame; Loc = location of the located object; CR = correct response; T = true; F = false.

3.3 Performance on spatial language measures (Study 1)

3.3.1 Predictions

People use appropriate spatial terms to describe spatial relations between objects in the environment on a daily basis. Therefore, healthy adults' performance on naming (static and dynamic) spatial relations (Spatial Naming Test) was expected to be positively skewed. Based on evidence that people are able to mentally represent and assign appropriate spatial terms for spatial relations under different spatial frames of reference, including self-centred (relative), object-centred (intrinsic), and environment-centred (absolute) reference frames (Burgess, 2006; Carlson, 1999; Carlson-Radvansky & Irwin, 1993), well above chance performance was predicted in all conditions of the VCSRF. However, considering that egocentric processing can be directly accessed whilst allocentric processing requires coordination processes, allocentric conditions in the VCSRF task and the survey perspective in the Spatial Verbal Memory task were expected to be more challenging for participants. Therefore, we believe that this will be reflected on a discrepancy between performances in the different conditions of the VCSRF, and that the environment-centred condition would impose less accurate and slower performance compared to the other conditions. Similarly, in the Spatial Verbal Memory task we expected worse immediate and delayed recalls in the extrinsic survey condition compared to the person-centred route condition.

3.3.2 Participants

Fifty-one healthy young adults (55% females; age range = 18-38, *M* = 24.04, *SD* = 5.88 years; level of education range = 12-21, *M* = 13.90, *SD* = 3.16 years) were recruited from the local community of the University of East Anglia for the present pilot study. All participants spoke English as their first language and reported no history of neurological or psychiatric disorders, or any other condition that could affect cognition. All participants had normal or corrected to normal vision and hearing. Each participant gave informed consent and received course credits or monetary compensation for participation. Ethical clearance was obtained by the local ethics committee.

3.3.3 Procedure

Testing took place on an individual basis and lasted approximately 30 min. For each spatial language measure, the standard administration and scoring procedures were followed as described in Section 3.2. The order of task administration was invariant for all participants. First, participants were administered the SVF task, and their responses were recorded with a voice recorder. Performance was based on the total number of correct words describing locative spatial relations generated in one minute. Next, participants heard the route and then the survey descriptions of the SVM task, and were asked to repeat each one immediately after hearing them. Their responses were recorded with a voice recorder, and performance was based on the total number of correctly recalled units for each story (route vs survey condition, immediate recall trial). Then, participants completed the SNT, starting with Part A for static spatial relations followed by Part B for dynamic spatial relations. The number of correct responses in each part was calculated as an index of naming accuracy, while the time to complete each part was recorded as an index of naming speed. Composite accuracy and speed scores for the SNT were calculated as the sum of scores from Parts A and B. Next, participants were administered the self-centred, the third-person-centred, the object-centred, and the environment-centred conditions of the VCSRF task. Accuracy of performance was based on the total number of correctly judged statements in each condition, while time to complete each condition served as an index of speed of performance. Composite accuracy and speed scores for the VCSRF were calculated as the sum of scores from each condition. Finally, participants were asked to recall the route and survey descriptions of the SVM task, while they were recorded with the use of a voice recorder, and performance was based on the number of correctly recalled units in each condition (route vs survey condition, delayed recall trial).

3.3.4 Results

Potential discrepancies among the different conditions within the SNT, SVM, and VCSRF tasks were examined separately by applying a series of one-way ANOVAs with condition (SNT: static, dynamic; SVM: route, survey; VCSRF: self-centred, third-person-centred, object-centred, environment-centred) as a within-subjects factor. Paired-samples *t* tests were conducted in order to follow-up significant main effects when appropriate. For accuracy scores in the SNT, SVM, and VCSRF tasks, the proportion of accurate/correct responses was calculated. Performance based on accuracy scores and speed scores for all spatial language measures is presented in Table 5. Figures 5-8 show the frequency distributions of the accuracy scores on each measure.

Table 5. *Performance on Each Spatial Language Measure*

	Score			
Measure	*M*	*SD*	*Minimum*	*Maximum*
Spatial verbal fluency (number of words)	14.33	3.72	8.00	24.00
Spatial naming (Tot): Accuracy (% correct)	91.14	4.90	80.00	100.00
Spatial naming (Tot): Speed (sec)	165.25	38.95	91.00	274.00
Static: Accuracy (% correct)	88.95	6.41	73.00	100.00
Static: Speed (sec)	90.45	23.81	47.00	160.00
Dynamic: Accuracy (% correct)	93.33	5.37	77.00	100.00
Dynamic: Speed (sec)	75.00	16.08	44.00	114.00
Spatial verbal memory				
Route description				
Immediate recall (% correct)	57.49	15.47	24.00	92.00
Delayed recall (% correct)	54.67	17.20	24.00	92.00
Survey description				
Immediate recall (% correct)	49.96	15.29	16.00	80.00
Delayed recall (% correct)	48.31	14.89	12.00	84.00
VCSRF (Tot): Accuracy (% correct)	95.22	4.84	78.00	100.00
VCSRF (Tot): Speed (sec)				
Self-centred: Accuracy (% correct)	100.00	0.00	100.00	100.00
Self-centred: Speed (sec)	49.74	6.15	37.00	69.00
Third-person-centred: Accuracy (% correct)	98.41	5.71	63.00	100.00
Third-person-centred: Speed (sec)	52.80	8.29	31.00	77.00
Object-centred: Accuracy (% correct)	97.18	9.12	63.00	100.00
Object-centred: Speed (sec)	48.35	6.08	37.00	68.00
Environment-centred: Accuracy (% correct)	86.64	14.89	50.00	100.00
Environment-centred): Speed (sec)	73.51	12.72	34.00	98.00

Note. Tot = total score; VCSRF = verbal comprehension in spatial reference frames; *N* = 51.

3.3.4.1 Spatial verbal fluency

In the SVF task, most participants (66.8%) produced 11 to 18 words describing locational spatial relations, with a mean of 14.33 (*SD* = 3.72) words (Figure 5).

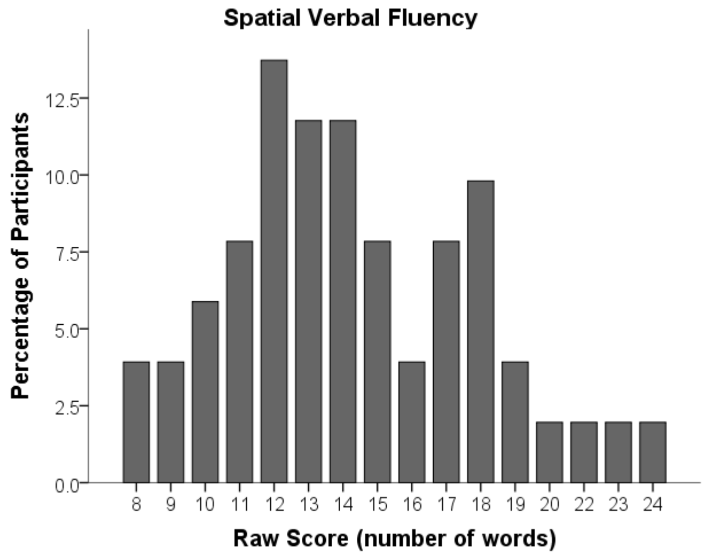


Figure 5. Frequency distribution of the number of words produced in the Spatial Verbal Fluency task.

3.3.4.2 Spatial naming

As expected, accuracy of performance on the SNT ranged well above chance levels, since all participants named accurately at least 24 out of the 30 spatial relations included in the task (Figure 6). The range of naming accuracy was similar for static and dynamic spatial relations (static: 73% - 100%; dynamic: 77% - 100%). However, naming accuracy was significantly higher for dynamic spatial relations (raw score: M = 14.00, SD = .80) compared to static spatial relations (raw score: M = 13.34, SD = .96), as indicated by a significant main effect of Trial Type (static vs dynamic spatial relations), $F(1, 50) = 22.34$, $p < .001$, partial $\eta^2 = .31$. Analysis also revealed a large main effect of Trial Type (static vs dynamic spatial relations) on naming speed, $F(1, 50) = 77.21$, $p < .001$, partial $\eta^2 = .61$, with participants being faster in naming dynamic (speed range = 44.00 – 114.00, M = 75.00, SD = 16.08 sec) compared to static (speed range = 47.00 – 160.00, M = 90.45, SD = 23.81 sec) spatial relations.

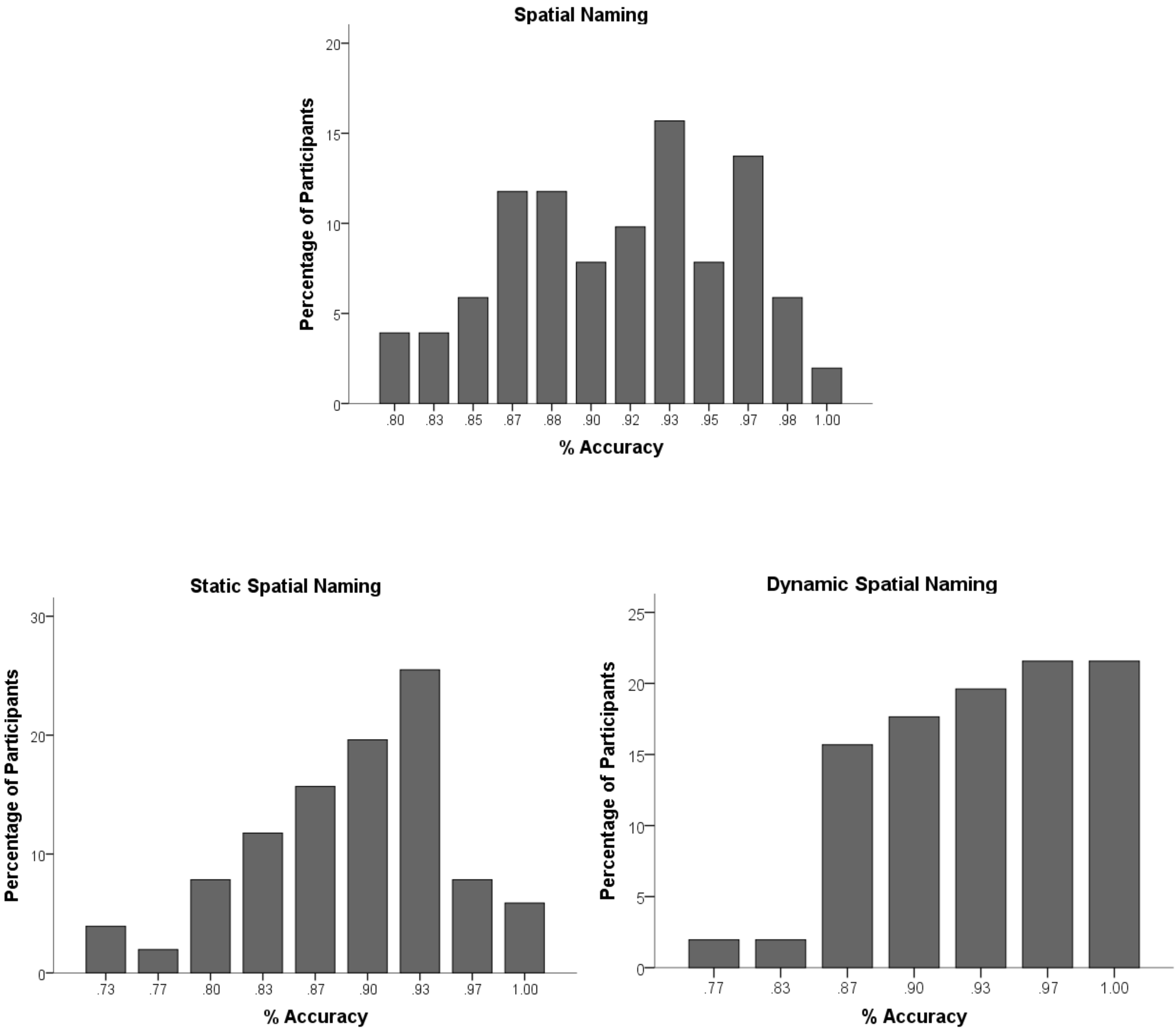


Figure 6. Frequency distributions of accuracy of performance in the Spatial Naming Test (Upper panel: composite score; Left panel: static spatial relations; Right panel: dynamic spatial relations).

3.3.4.3 Spatial verbal memory

In the Spatial Verbal Memory task (Figure 7), there was a significant main effect of the Perspective, $F(1, 50) = 15.54$, $p < .001$, partial $\eta^2 = .24$, with participants immediately recalling more information in the route (raw score: $M = 14.37$, $SD = 3.86$) compared to the survey (raw score: $M = 12.49$, $SD = 3.82$) description. Similarly, participants recalled more information in the route (raw score: $M = 13.67$, $SD = 4.30$) versus the survey (raw score: $M =$

12.08, *SD* = 3.72) description after a ~ 25 min delay, $F(1, 50) = 9.05$, $p = .004$, partial $\eta^2 = .15$. Moreover, participants recalled more information immediately than after a 25 min delay in the route description, $F(1, 50) = 9.67$, $p = .004$, partial $\eta^2 = .15$, but not in the survey description, $F(1, 50) = 1.91$, $p = .173$, partial $\eta^2 = .04$. On average, participants' recall of spatial information presented from a route perspective decreased from 57.49% to 54.67% after a short period of time, while their recall of spatial information presented from a survey perspective was slightly poorer in the delayed condition, but the difference did not reach significance.

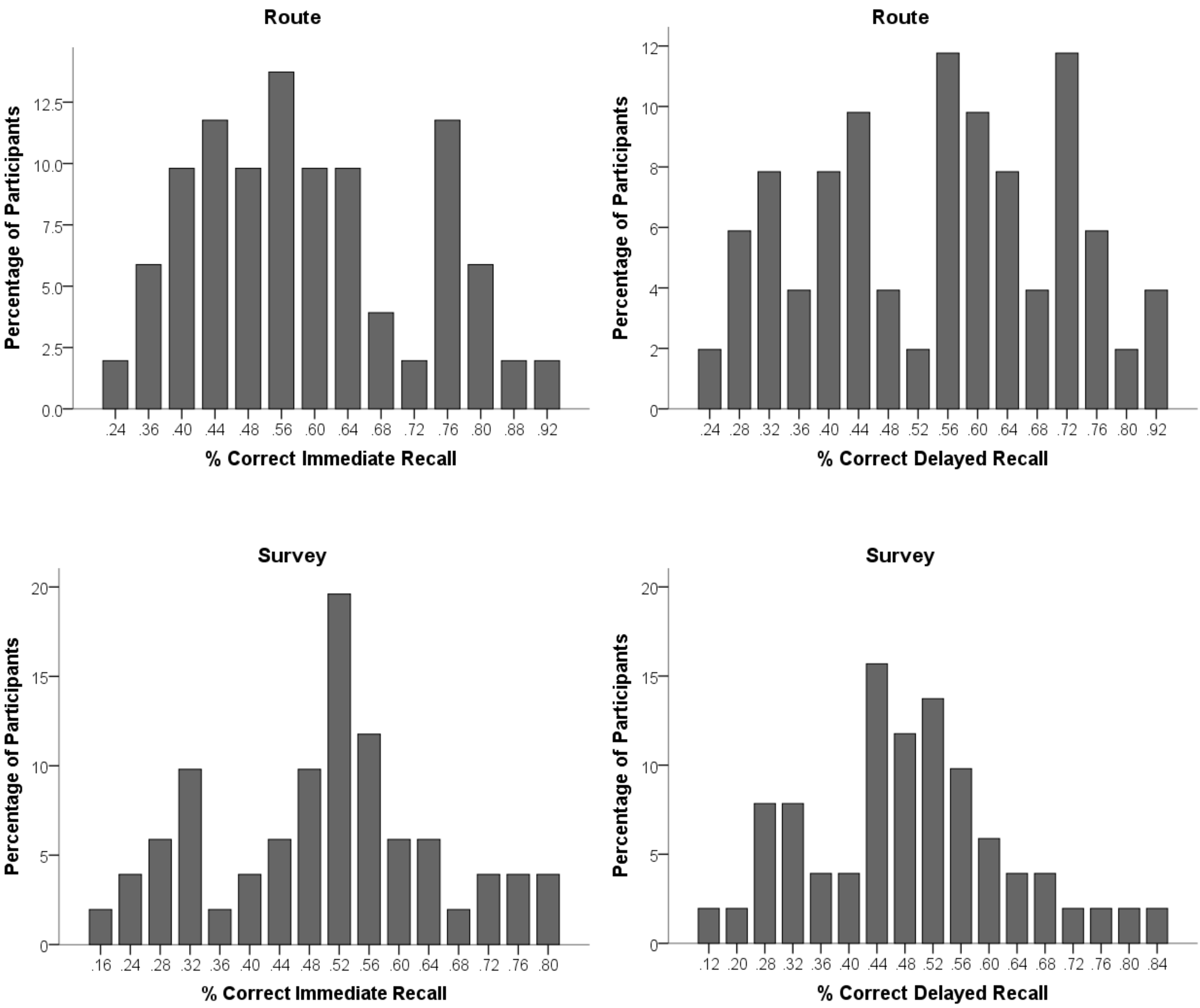


Figure 7. Frequency distributions of performance in the Spatial Verbal Memory task (upper panels: route perspective; lower panels: survey perspective; left panels: immediate recall; right panels: delayed recalls).

3.3.4.4 Verbal comprehension in spatial reference frames

As predicted, participants' accuracy of performance in the VCSRF (Figure 8) ranged well above chance levels, as their mean composite score was 60.94 (SD = 3.10; proportional M = 95.22, SD = 4.8). Accuracy in the self-centred relative condition reached ceiling levels (i.e., 100% of participants correctly verified 100% of the target spatial relations), and approached ceiling levels in the third-person-centred condition (M = 15.74, SD = .91; proportional M = 98.41) as well as in the object-centred condition (M = 15.55, SD = 1.46; proportional M = 97.18). However, accuracy was substantially lower in the environment-centred condition (M = 13.86, SD = 2.38; proportional M = 86.64). We found a significant Trial Type main effect on accuracy scores, $F(3, 150) = 22.78$, $p < .001$, partial $\eta^2 = .31$, which was followed up with paired samples t tests. Analyses revealed significant discrepancies between the self-centred and object-centred conditions, $t(50) = 2.21$, $p = .032$, the self-centred and environment-centred conditions, $t(50) = 6.40$, $p < .001$, as well as between the third-person-centred and environment-centred conditions, $t(50) = 5.19$, $p < .001$, and the object-centred and environment-centred conditions, $t(50) = 4.34$, $p = .001$. There was a tendency for a significant difference between the self-centred and third-person-centred relative conditions, which did not reach statistical significance, $t(50) = 1.99$, $p = .052$, while accuracy in the third-person-centred condition ranged at similar levels with accuracy in the object-centred condition, $t(50) = .93$, $p > .250$. Moreover, there was a large Trial Type main effect on speed scores, $F(3, 150) = 223.36$, $p < .001$, partial $\eta^2 = .82$. Paired samples t tests indicated substantial differences between all conditions except between self-centred and object-centred, $t(50) = 1.06$, $p = .067$ [self-centred and third-person-centred: $t(50) = -3.91$, $p < .001$; self-centred and environment-centred: $t(50) = -16.34$, $p < .001$; third-person-centred and object-centred: $t(50) = 5.16$, $p < .001$; third-person-centred and environment-centred: $t(50) = -16.96$, $p < .001$; object-centred and environment-centred: $t(50) = -17.75$, $p < .001$; Table 5]. Participants were faster in responding in the self-centred (M = 49.74, SD = 6.15 sec) and object-centred (M = 48.35, SD = 6.07 sec) conditions, relatively slower in the third-person-centred condition (M = 52.80, SD = 8.29 sec), and markedly slower in the environment-centred condition (M = 73.50, SD = 12.72 sec).

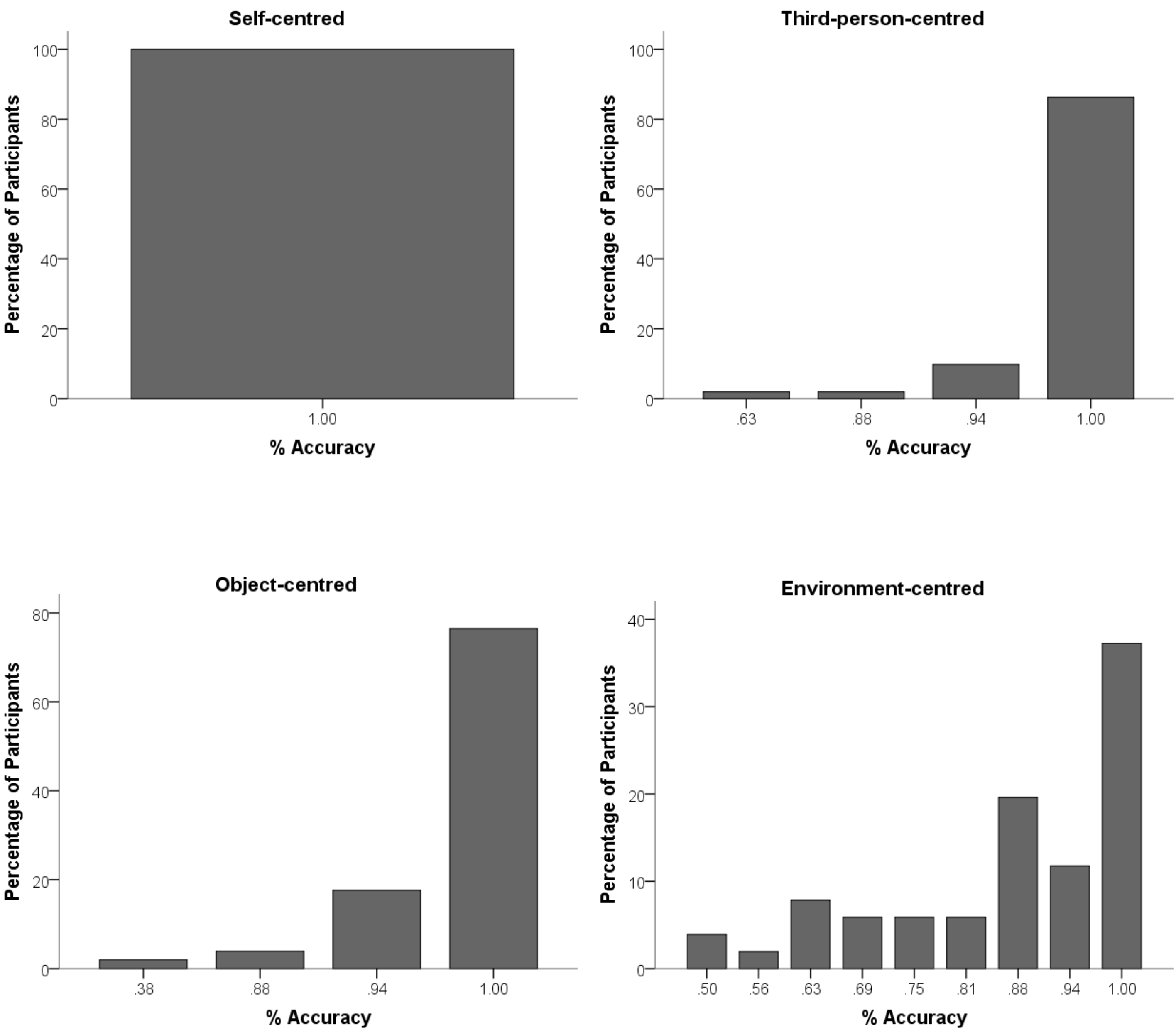


Figure 8. Frequency distributions of accuracy of performance in all conditions of the Verbal Comprehension in Spatial Reference Frames task.

3.4 Test-retest reliability and practice effects (Study 2)

3.4.1 Participants

Thirty-two healthy adults (18 females), ranging in age from 21 to 54 years (age: *M* = 36.3, *SD* = 10.21 years; level of education: range = 13–21, *M* = 15.03, *SD* = 2.92 years), were recruited from the University of East Anglia local community for this study. All participants spoke English as their first language and reported no history of neurological or psychiatric disorders, or any other condition that could affect cognition. All participants had normal or corrected to normal vision and hearing. Each participant gave informed consent and received monetary compensation for participation. Ethical clearance was obtained by the local ethics committee.

3.4.2 Procedure

All participants were administered the novel spatial language measures (i.e., SVF, SNT, SVM, VCSRF), on two occasions, with a testing interval of between 2 and 24 weeks. Testing took place on a one-to-one basis and each testing session lasted approximately 30 mins. For each spatial language measure, the standard administration and scoring procedures were followed as described in Section 3.2. The order of task administration was invariant for all participants, was the same across the two testing sessions, and was similar to Study 1 (briefly: SVF, immediate recall of the SVM, SNT, VCSRF, delayed recall of the SVM; see Section 3.3.3 for more details).

Spatial language performance across the two sessions was examined as following: the number of correct words generated in the SVF task; the number of correct responses (accuracy) and time to complete (speed) Parts A and B of SNT (note that composite accuracy and speed scores for the SNT were also calculate); the correctly recalled units of the route and survey conditions in the immediate and delayed trials of the SVM; the correct responses (accuracy) and time to complete (speed) each condition (self-centred, third-person-centred, object-centred, environment-centred) of the VCSRF (note that composite accuracy and speed scores for the VCSRF were also calculated).

3.4.3 Results

Pearson product-moment correlations between scores across the two testing sessions were calculated in order to examine test-retest reliability of each spatial language measure. Test-retest means and reliability coefficients are presented separately for each measure in Table 6.

Paired-samples *t*-tests were performed to compare mean scores between the two sessions for each measure. Results revealed that speed scores were subject to a practice effect. Participants performed faster on the second administration of the Spatial Naming Test [total speed: $t(31) = 5.09$, $p < .001$; speed in static spatial naming: $t(31) = 5.08$, $p < .001$; speed in dynamic spatial naming: $t(31) = 4.17$, $p = .001$] and the Verbal Comprehension in Spatial Reference Frames task [self-centred: $t(31) = 8.35$, $p < .001$; third-person-centred: $t(31) = 3.24$, $p = .004$; object-centred: $t(31) = 4.88$, $p < .001$; environment-centred: $t(31) =$

3.60, p = .002]. Significant practice effects were also noticed on the delayed recall of the route description, $t(31) = -3.19$, p = .005, and the immediate recall of the survey description, $t(31) = -2.47$, p = .023, in the Spatial Verbal Memory task, with participants performing better on the second administration. Finally, no practice effects were detected on Spatial Verbal Fluency, nor on accuracy scores of the Spatial Naming Test and the VCSRF ($p > .050$).

Table 6. *Test-Retest Data and Correlation Coefficients for all Novel Spatial Language Measures*

	Session 1		Session 2		
	M	*SD*	*M*	*SD*	r_{tt}
Spatial verbal fluency	16.65	3.61	16.80	2.74	.74**
Spatial naming (Tot): Ac	28.15	1.19	28.30	0.87	.87**
Spatial naming (Tot): Sp	178.80	37.59	153.25	28.58	.80**
Static: Ac	14.00	0.58	14.07	0.43	.81**
Static: Sp	99.80	22.69	82.30	17.01	.73**
Dynamic: Ac	14.15	0.82	14.25	0.65	.94**
Dynamic: Sp	78.50	14.07	70.95	13.50	.83**
Spatial verbal memory					
Route					
Immediate recall	16.75	3.22	17.25	3.40	.93**
Delayed recall	16.05	3.50	17.10	3.41	.91**
Survey					
Immediate recall	14.25	3.46	15.25	3.64	.87**
Delayed recall	14.25	3.69	15.00	3.21	.82**
VCSRF (Tot): Ac	61.80	2.68	61.90	2.99	.86**
VCSRF (Tot): Sp	228.50	34.74	205.65	26.92	.87**
Self-centred: Ac	16.00	0.00	16.00	0.00	—
Self-centred: Sp	51.00	6.90	45.20	6.90	.90**
Third-person-centred: Ac	15.85	0.36	15.85	0.36	.85**
Third-person-centred: Sp	56.40	12.47	51.15	10.22	.81**
Object-centred: Ac	16.00	0.00	16.00	0.00	—
Object-centred: Sp	48.50	5.52	44.65	4.23	.77**
Environment-centred: Ac	14.05	2.64	14.05	2.79	.88**
Environment-centred: Sp	72.60	15.31	64.65	12.52	.76**

Note. Tot = total score; Ac = accuracy score; Sp = speed score; VCSRF = verbal comprehension in spatial reference frames; ** $p < .001$ (N = 32).

3.5 Discussion

Spatial language refers to the ability to verbally communicate spatial information, such as where objects are located, forming a unique natural linkage between linguistic and perceptual representations. Despite its importance, and despite the large variety of standardized cognitive measures across the verbal and the visuospatial domain, there are no available standardized measures assessing spatial language abilities.

In an attempt to contribute towards filling this gap, we developed four new tests specifically designed to assess different aspects of spatial language processing, focusing on production, memory, and comprehension, and established their test-retest reliability. Two tasks were developed for the assessment of spatial-verbal production: a verbal fluency task requiring free generation of words describing locative spatial relations (SVF) and a naming task for static and dynamic spatial relations (SNT). The task assessing episodic spatial-verbal memory involved immediate and delayed recall trials of spatial descriptions presented either from a route or a survey perspective (SVM). The task assessing spatial-verbal comprehension involved judging statements of spatial descriptions under four different spatial reference frames: a self-centred, a third-person-centred, an object-centred, and an environment-centred spatial reference frame (VCSRF).

For the first study, data obtained from a sample of 51 healthy young adults were used. As expected, we found young participants to be efficient in using appropriate spatial prepositions and prepositional phrases to describe accurately both static and dynamic spatial relations between geometric objects. Distributions of naming accuracy were similar for static and dynamic relations, however, young adults were more accurate and faster in naming dynamic spatial relations, resulting in a more skewed distribution for the dynamic condition. Even though differences between static versus dynamic spatial abilities have been largely neglected (Hegarty & Waller, 2005), there is some evidence suggesting that these two domains of spatial processing may be relatively distinct (Carroll, 1993; Conteras, Colom, Hernández, & Santacreu, 2003). Göksun et al. (2013) found no effects of task type (static vs dynamic) on spatial naming accuracy in patients with left or right hemispheric lesions, nor in healthy controls, however, the stimuli used in that study were concrete everyday objects and the targeted spatial relations were limited (four in the static and five in the dynamic condition, respectively). In our study, the discrepancy found between naming static and dynamic spatial relations as evidenced both in accuracy and speed scores, may have resulted from the more complex nature of some static relations compared to the dynamic (e.g., *among*), as well as to the richer configuration content in the static condition, as the pictures included a set of non-target relations in order to create a variety of differentiable relations. It is possible that the presence of non-target spatial relations may resulted in a higher cognitive load by requiring inhibition of the non-targeted relations.

In line with the predictions, young participants showed above chance performance in comprehension of descriptions of spatial relations under different reference frames. These results confirm that spatial relations between two objects can be effectively represented based on either an observer's viewpoint, or with respect to an object's axial system, or based on external environment points (Carlson, 1999; Levinson, 1996, 2003; Miller & Johnson-Laird, 1976). Accuracy was at ceiling in the self-centred condition and approximated ceiling levels in the third-person-centred and object-centred conditions. As predicted, performance was less accurate and slower in the environment-centred condition compared to the other conditions, which is likely to reflect a higher cognitive load associated to additional coordination processes between the two spatially-related objects and an external environmental point. Similarly, in the Spatial Verbal Memory task, young adults exhibited better verbal recollection for spatial descriptions presented from a person-centred route perspective than for survey descriptions, both in the immediate and delayed conditions. Past investigations have revealed that viewer-, object-, and landmark-centred processing of location involves differential spatial abilities that are, at least to some extent, supported by different brain areas (e.g., Committeri et al., 2004; for reviews see Burgess, 2006; Galati et al., 2010). Moreover, our findings are in alignment with the assumption that allocentric spatial representation may be more demanding than egocentric representation as it requires additional integration processes (Klatzky, 1998). This assumption applies particularly in Western cultures which favour self-centred coordinate systems.

Finally, we provided data for the test-retest reliability and practice effects in a group of 32 healthy adults with a testing interval of between 2 weeks to 6 months, on all performance scores of the spatial language measures. Our data demonstrated excellent test-retest reliability of all new measures, with moderately high to very high correlation coefficients for accuracy scores ($r_{tt} =$ .74 to .94) as well as for speed scores ($r_{tt} =$ .73 to .90). Furthermore, our data regarding potential practice effects on all spatial language measures indicated that speed of performance in the Spatial Naming Test and the VCSRF task generally improved between the two test sessions. This result is not surprising, as speed scores are known to be particularly sensitive to practice effects (Strauss et al., 2006). We also found a low practice effect on the Spatial Verbal Memory task, with participants recalling more units on the second administration, in accordance to the well-documented practice effects in verbal recall tasks (for a review, see Cepeda, Pashler, Vul, Wixted, & Rohrer, 2006). On the other hand, accuracy scores in the SNT and VCSRF tasks did not change on the second administration, supporting that these tasks provide consistent results over time.

To summarize, we developed four new tests assessing spatial-verbal production (SVF, SNT), episodic memory (SVM), and comprehension under different spatial reference frames (VCSRF), and established their test-retest reliability. These brief and simple paper-and-pencil tests can provide a useful means of assessing different aspects of spatial language processing, an important facet of cognition that, so far, has not been investigated thoroughly in typically developing adults and in clinical populations with cognitive deficits.

The second part of the present thesis focuses on cognitive functioning across the adult-lifespan building on the measures reported above. Chapter 4 provides a wide literature review regarding the ageing effects on various core and higher cognitive processes across the verbal and visuospatial domain. Chapter 5 presents results from a large dataset obtained from a sample of healthy adults aged between 18 to 85 years. These include further information about the psychometric properties of each novel spatial language test, as well as their concurrent and construct validity by a series of hypothesis-driven correlational analyses and an exploratory factor analysis. Moreover, Chapter 5 examines the effects of demographic factors that may affect performance and subsequently provides adjusted normative data for the English population. Next, the adult-lifespan trajectories of spatial verbal production, memory, and comprehension are provided in detail and are contrasted against the trajectories of verbal and visuospatial abilities. Finally, Chapter 5 examines how the relationships between spatial language abilities and certain aspects of cognition may change across the adult-lifespan.

Part II

Ageing

Chapter 4 Introduction to ageing

4.1 Relevance

Population ageing is a global phenomenon that results from a combination of declining birth rates and increasing life expectancies. According to the UN (2013), the global median age has risen from 24 years in 1950 to 29 in 2010, and is expected to increase to 36 years by 2050. Moreover, the proportion of the world's population aged 60 years or over increased from 8% in 1950 to 12% in 2013, and is expected to account for 21% of the world's population by 2050. Meanwhile, the median age in more developed regions of the world increased more rapidly between 1950 and 2010, from 28 years to 40 years (UN, 2013). The latest report by Eurostat (2015) indicated that the median age of the European population was 43 years in 2015 and is projected to increase to 47 years by 2040, while it is estimated that those aged 65 years or over will account for almost 28.7% of the European population by 2080, compared to 18.9% in 2015.

The effects of the continuous ageing of the world's population on society are enormous, as it results in increased old-age dependency ratios, higher burden on the shrinking working-age population, greater public spending on health care, and overall decline in economic growth. Using probabilistic population forecasts, some researchers estimate that the speed of ageing is likely to have an accelerating rate over the coming decades (Lutz, Sanderson, & Scherbov, 2008), while age-related disorders that affect cognition, such as Alzheimer's disease, are becoming dramatically more frequent (Abbott, 2011). Therefore, it is of critical importance to identify how different aspects of cognitive functioning may change across the adult life span, as these changes can significantly impact upon daily functioning, and, in addition, they can help us distinguish normal from pathological ageing.

4.2 Cognition in healthy ageing

4.2.1 Models of cognitive ageing

Numerous theories and models have been proposed to explain age-related declines in cognitive functioning (see Reuter-Lorenz & Park, 2010, for a review). The most influential and empirically tested models in neuropsychology have focused on processing speed and on executive functions. In 1996, Timothy Salthouse introduced the processing speed theory, which asserts that the age-related decline in several cognitive processes can be accounted for by the generalized slowing of cognitive processing. According to Salthouse (1996), any complex mental task is executed by multiple cognitive processes, and task completion may be aversively affected when one or more of these operations cannot be performed quickly enough ("limited time mechanism"), as in complex perceptual tasks, or when products of early processing stages cannot longer be accessed during later processing stages ("simultaneity mechanism"), as in working memory tasks which require cognitive manipulation of actively maintained material (see also Salthouse, 2000). Several researchers have adopted Salthouse's theoretical framework to explain age changes in memory and spatial abilities (e.g., Finker, Reynolds, McArdle, & Pedersen, 2007). Slower processing speed is likely to be the most robust finding of cognitive ageing, leading some researches to propose the use of processing speed tasks as biomarkers of cognitive ageing (Deary, Johnson, & Starr, 2010). From a neural standpoint, the generalized slowing of cognition in older adults is thought to root in a global deterioration of white matter integrity throughout the brain (e.g., Borghesani, et al., 2013; Sullivan, Rohlfing, & Pfefferbaum, 2010; Ylikoski et al., 1993).

On the other hand, some theories stress that local structural and functional changes in frontal areas of the brain, such as significant volume reduction, result in deterioration of executive functioning, which in turn mediate more general cognitive deficits (see the frontal-executive theory of ageing by West, 1996). Executive functions constitute a cluster of attentionally effortful mental processes required in our effective adaptation to novel or demanding situations (see Diamond, 2013, for a recent review). Traditionally, executive functions are divided into three core categories: inhibition of dominant or prepotent responses, shifting between mental sets (mental flexibility), and updating and monitoring of working memory representations (Miyake et al., 2000). Executive functions also include abilities of goal formation, initiation and execution of goal-directed plans (Jurado & Rosselli, 2007), as well as affective regulation (Stuss & Alexander, 2000). The executive system has been associated with so many skills necessary for adaptive human behaviour, that it has been suggested that as long as they are intact, a person can remain independent and productive even after sustaining other forms of cognitive impairment (Lezak et al., 2012). Findings from a considerable number of studies indicate that executive functions are particularly sensitive to age decline (e.g., De Luca et al., 2004; Kane et al., 2004; Zelazo, Craik, & Booth, 2004; Robbins et al., 1998; for reviews see Hedden & Gabrieli, 2004; Jurado & Rosselli, 2007), however, it has been difficult to exclude whether processing speed underpins several of the age-related changes in cognitive abilities (Fisk & Sharp, 2004). Nevertheless, there is substantial evidence to suggest that age has a unique effect on executive abilities beyond that accounted for by the slowing in processing speed (e.g., Albinet, Boucard, Bouquet, & Audiffren, 2012; Keys & White, 2000).

The brain of older adults is characterized by a generalized grey matter atrophy (Oh, Madison, Villeneuve, Markley, & Jagust, 2013) and deterioration of white matter integrity (see Madden, Bennett, & Song, 2009; Gunning-Dixon et al., 2009; Kennedy & Raz, 2009, for reviews). However, both cross-sectional (Fjell et al., 2009; Moffat et al., 2007) and longitudinal (Mungas et al., 2005; Raz et al., 2010) studies have revealed a more prominent volumetric reduction in the prefrontal cortex, superior parietal, and inferior temporal cortices (see Hedden & Gabrieli, 2004; Jagust, 2013 for reviews), as well as in the hippocampi (e.g., Apostolova et al., 2012; Fjell et al., 2014; Raz et al., 2010; Reuter-Lorenz, 2000).

Meanwhile, several functional alterations have been systematically observed to occur with increasing age (see Turner & Spreng, 2012 for a meta-analysis regarding executive functions). One of the most robust changes observed is functional dedifferentiation, which refers to the loss of regional specialization of neural circuits. For example, younger adults present predominantly left hemisphere activation during verbal working memory tasks and right lateralized activation during visuospatial working memory tasks, whereas older adults exhibit a global pattern of bilateral anterior activation for both memory types (Reuter-Lorenz, et al., 2000; Schneider-Garces et al., 2010). Apart from decreased memory-related recruitment of medial temporal areas (Guthness et al., 2005), decreased processing neural specificity among older adults has also been reported for visual (Voss et al., 2008) and motor areas (Bernard & Seidler, 2012). The hemispheric asymmetry reduction in older adults (HAROLD) model proposed by Cabeza (2002) posits that the increased symmetrical hemispheric activation in the prefrontal cortex may result from a global reorganization of neurocognitive networks that may reflect dedifferentiation and compensatory processes.

In addition to the age-related alteration in hemispheric specialization, neuroimaging data also stress that older adults exhibit greater extent of brain activation than younger adults for similar levels of task difficulty in memory paradigms, especially in anterior regions (e.g., Cappell, Gmeindl, & Reuter-Lorenz, 2010; Nagel et al., 2009; Schneider-Garces et al., 2010). The overactivation in frontal areas coupled with a reduced activity in posterior areas has led to the posterior-anterior shift in ageing (PASA) model proposed by Davis and colleagues (2008). One possible explanation of this phenomenon may be that older adults need to recruit additional neuronal resources even at lower cognitive loads than younger adults, leaving limited resources for demanding cognitive tasks, and thus leading to poorer performance (Reuter-Lorenz & Cappell, 2008). An alternative plausible interpretation is that the age-related overactivation is compensating for processing deficiencies elsewhere, including decreased connectivity in resting-state networks that involve the frontal, parietal, and temporal regions (Damoiseaux et al., 2008), by utilizing additional circuits to optimize performance (Reuter-Lorenz & Cappell, 2008). After all, overactivation in older adults has been associated with better performance across a range of tasks such as working memory (e.g., Gutchess et al., 2005) and semantic retrieval (Persson et al., 2007; see Eyler, Sherzai, & Jeste, 2011 for a review).

The compensation-related utilisation of neural circuits hypothesis (CRUNCH model) proposed by Reuter-Lorenz & Cappell (2008) posits that declining neural efficiency leads older adults to engage more neural circuits than younger adults in order to meet task demands, and thus are likely to show bilateral overactivation in various brain areas. In line with the CRUNCH model, Berlinger, Danelli, Bottini, Sberna, and Paulesu (2013), found an age-related increase of bilateral neural activation during linguistic (naming and sentence-judgement tasks) tasks and episodic verbal recognition tasks, which was not restricted in frontal areas. By manipulating the cognitive load in working memory paradigms, Schneider-Garces et al. (2010) found that individuals with lower memory capacity are exhibiting increased neural activation, regardless of age, supporting Reuter-Lorenz & Cappell's (2008) hypothesis of compensatory recruitment of supplementary neural circuits during challenging tasks.

The scaffolding theory of ageing and cognition (STAC model; Park & Reuter-Lorenz, 2009; Reuter-Lorenz & Park, 2014) attempts to provide an integrative account of age-related changes across the lifespan, positing that as the brain is challenged by structural (i.e., grey matter atrophy, white matter deterioration, and several neurophysiological alterations) and functional (i.e., dedifferentiation of specialized cognitive networks and dysregulation of default mode networks) changes across the adult lifespan, it responds by employing alternative neural circuits (compensating scaffolds) that may operate less efficiently than the specialized networks of younger adults, but may also permit individuals to maintain a good level of cognitive functioning. The structural, neurophysiological, and functional changes occurring in the ageing brain progress dynamically, as they are subject to life experiences and environmental influences (Stern, 2012). Therefore, the SCAT model predicts efficient cognitive functioning when enhanced compensatory scaffolding occurs, for example in highly educated individuals (Reuter-Lorenz & Park, 2014). This view is in accordance to the cognitive reserve hypothesis championed by Stern (2002, 2009, 2012), which postulates that experience-mediated individual differences in cognitive processes or/and their underlying neural networks allow some people to cope better than others with brain pathology.

Summary. To summarize, accumulating evidence indicates that older adults exhibit a general slowing in cognitive processing as well as deficits in executive functions, including impairments in working memory, inhibitory control, and mental flexibility. These cognitive changes have been associated with age-related structural and functional alterations of the brain, including deterioration of the grey and white matter, dedifferentiation of specialized neurocognitive circuits, and bilateral neural overactivation, particularly in anterior regions of the brain. Several contemporary neurocognitive models of ageing suggest that a dynamic functional reorganization of the ageing brain is likely to take place in order to compensate for the age-related deterioration of cognitive resources and their neural underpins. The next sections of this chapter provide a literature review on cognitive processing within the visuospatial and verbal domain across the adult lifespan and in ageing.

4.2.2 Language abilities in ageing

In spite of the neural changes, the sensory impairments, and the general slowing in cognitive operations, many language skills that involve semantic, phonological, syntactic and grammatical processes, remain well-preserved in old age. Nevertheless, linguistic processing amongst older adults is characterized by an asymmetry between language comprehension and language production. More particularly, lexical knowledge and word/semantic recognition as well as general language comprehension (receptive language processing) remain relatively stable in old age, whereas language production and encoding of new verbal information are declined (Burke & Shafto, 2008; Shafto & Tyler, 2014; Stine-Morrow & Shake, 2009).

Verbal comprehension. Healthy older adults typically communicate with good effectiveness. Speech and language processing are largely intact in older adults perhaps because the linguistic knowledge and the procedural rules for implementing this knowledge remain well preserved in normal ageing (Wingfield & Grossman, 2006). Under normal conditions, younger and older adults do not differ in comprehension of spoken language, even in individuals with mild-to-moderate hearing loss (Wingfield, McCoy, Peelle, Tun, & Cox, 2006). However, speech comprehension for highly syntactically complex sentences (i.e., object-relative instead of subject-relative sentences) may be more challenging for older individuals, especially during rapid speech rates (Wingfield et al., 2006), perhaps due to the increased demands on the available working memory resources (Salthouse & Craik, 2000).

Nevertheless, language holds a special place among preserved functions in normal ageing. This is not so surprising if we consider that language starts developing from a very young age with no formal training despite its complexity, is actively practiced on a daily basis continuously throughout the lifespan, and is highly supported by procedural knowledge which is accessed effortlessly. Good language performance is largely underpinned by the same processes across the adulthood (Shafto & Tyler, 2014), carried by a rich network of brain regions, which apart from the left perisylvian regions includes bilateral extrasylvian cortical regions (e.g., Peelle, Troiani, Wingfield, & Grossman, 2009), allowing sufficient compensation to operate at an extraordinarily good level in older age (Wingfield & Grossman, 2006). Impairments in verbal comprehension that occur under difficult processing conditions have been primarily attributable to sensory loss or working memory limitations and not to impairments in basic language capacities per se (for a review see Wingfield & Stine-Morrow, 2000). Additionally, sensory loss (auditory and visual, respectively) may consume some of the cognitive resources (i.e., attention) that would otherwise be used on language processing (Stine-Morrow & Shake, 2009).

Semantic and episodic verbal memory. Numerous studies have revealed that episodic memory, as assessed by tasks of episodic retrieval for verbal information (such as short stories or lists of words), is particularly sensitive to age-related decline (Luo & Craik, 2008; Tromp, Dufour, Lithfous, Pebayle, & Despres, 2015). The average onset of decline in performance of verbal memory tasks is uncertain; some studies indicate a linear deterioration across the adult lifespan, beginning in young adulthood (Li et al., 2004; Park et al., 2002). However, other studies suggest that episodic memory performance remains relatively stable until about 60-65 years of age, after which accelerating decline is observed (Ronnlund et al., 2005). Episodic memory impairment is the most striking cognitive alteration in pathological ageing, particularly in individuals with Alzheimer’s disease (McKhann et al., 2011), and is largely associated with atrophy predominantly in the medial temporal areas and the hippocampus (Schwindt & Black, 2009). Frontal areas are crucial in controlling and organizing the encoding and retrieval of episodic memory information (Kramer et al., 2005). Contrary to younger adults, older adults spontaneously employ a limited repertoire of strategies that facilitate verbal encoding, such as mental imagery or sub-vocal rehearsal (e.g., Dunlosky & Hertzog, 2001). Meanwhile, multisensory and/or deep semantic encoding of novel verbal information may result in better performance in older adults (e.g., Craik & Jennings, 1992; Kalpouzos et al., 2009). Based on these findings while taking into account that the prefrontal cortex seems to be the first structure affected in typical ageing, before any apparent atrophy in the medial temporal and parietal areas occurs (Raz & Rodrigue, 2006), it has been suggested that the changes in the prefrontal cortex may actually underlie the age-related declines in episodic memory (see Tromp et al., 2015, for a comprehensive review).

However, not all forms of human memory are equally affected by advancing age. Accumulating evidence indicates that semantic memory and knowledge for all kinds of concepts is well preserved throughout the adult lifespan (Levine et al., 2002; Piolino, Desgranges, Benali, & Eustache, 2002). In fact, word knowledge may even improve across the adult lifespan (e.g., Kennedy et al., 2015; see Verhaeghen, 2003, for a meta-analysis). Semantic knowledge is supported by a widely-distributed network with the anterior temporal lobes at its central hub (see Patterson, Nestor, & Rogers, 2007; Simmons & Martin, 2009; Visser, Jefferies, & Lambon Ralph, 2009, for reviews and meta-analyses), which seems to be more resilient to ageing effects than the medial temporal areas, which are critical for learning novel episodic information (Jack et al., 1997; Rugg & Vilberg, 2013). Still, effective use of semantic knowledge during language production, especially in demanding situations, requires control processes associated with a large-scale network that includes prefrontal, posterior temporal, and parietal areas (Whitney, Kirk, O'Sullivan, Ralph, & Jeffries, 2011). As described next, older adults may be less efficient in certain aspects of language production.

Verbal fluency. Verbal fluency tasks require participants to generate as many words as possible within a limited amount of time, according to specific phonemic (e.g., words beginning with a specific letter, such as F, A, or S) or semantic (e.g., animals, actions) cues, in the absence of visual prompts. Therefore, apart from semantic knowledge, verbal fluency relies heavily on executive functioning as it requires effective use of retrieval and organization strategies (Strauss et al., 2006). Lesion studies (Baldo, Schwartz, Wilkins, & Dronkers, 2006; Markostamou, Tsapkini, Karakostas, & Kosmidis, manuscript in preparation) as well as functional neuroimaging studies with healthy adults (e.g., Birn et al., 2010; Gauthier, Duyme, Zanca, & Capron, 2009) have shown a left lateralized involvement of the temporal lobe and the dorsolateral prefrontal cortex during verbal fluency. Results from lesion studies also indicate that frontal lobe damage impairs phonemic fluency to a greater extent, while temporal lobe lesions may disproportionately impair semantic fluency (Baldo et al., 2006, see Henry & Crawford, 2004, for a meta-analysis). Moreover, switching between subcategories during verbal fluency is predominantly impaired after frontal lobe damage, while semantic fluency clustering is impaired after damage in the temporal lobe (Troyer, Moscovitch, Winocur, Alexander, & Stuss, 1998).

Most cross-sectional studies from different countries, including Japan (Abe et al., 2004), Canada (Tombaugh, Kozak, & Rees, 1999), Spain (Benito-Cuadrado et al., 2002; Pena-Casanova et al., 2009), Italy (Costa et al., 2014), Greece (Kosmidis et al., 2004), Sweden (Tallberg et al., 2008), Portugal (Cavaco et al., 2013), the UK (Harrison, Buxton, Husain, & Wise, 2000), the USA (Brickman et al., 2005; Gladsjo et al., 1999), and the Netherlands (Van Der Elst et al., 2006), have revealed that performance on verbal fluency tasks declines with age and improves with education. Existing data suggest that the effects of age on phonemic fluency are less pronounced compared to the effects of education, while semantic fluency is more susceptible to the effects of ageing compared to education (Brickman et al., 2005; Cavaco et al., 2013; Harrison et al., 2010; Kosmidis et al., 2004; Tallberg et al., 2008; Tombaugh et al., 1999; Troyer, 2000). According to a meta-analysis of 26 studies focusing on ageing, performance on phonemic verbal fluency improves until the third decade of life and remains constant until the 40s, while a mild decline is apparent from the 60s and accelerates through the 80s (Rodriguez-Aranda & Martinussen, 2006). On the other hand, semantic fluency seems to deteriorate rather gradually throughout the adult lifespan (e.g., Cavaco et al., 2013), although the decline is more prominent from the 60s onwards (e.g., Tombaugh et al., 1999). Notably, the spontaneous employment of clustering and switching strategies, that maximize word generation, is poorer with increasing age (Kosmidis et al., 2004; Troyer, 2000). This finding supports that older adults' low performance in cued word production may result from impoverished frontal control abilities, especially switching, rather than from diminished semantic knowledge.

Lexical retrieval. The tip-of-the-tongue phenomenon occurs when the meaning of a word is available but the phonological representation of the word cannot be accessed (Burke, MacKay, Worthley, & Wade, 1991). According to several studies, older individuals experience word-finding failures in the form of tip-of-the-tongue states during naturalistic speech more frequently than younger adults (Burke et al., 1991; Juncos-Rabadán, et al., 2006; Shafto, Burke, Stamatakis, Tam, & Tyler, 2007). The ageing effects on lexical retrieval abilities examined by confrontational naming tasks have been widely studied, however, reports are inconsistent. More specifically, some cross-sectional studies have reported a mild negative impact of increasing age on naming accuracy for objects and actions (e.g., Barresi, Nicholas, Connor, Obler, & Albert, 2000; Mackay, Connor, Albert, & Olber, 2002; Mortensen, Meyer, & Humphreys, 2008; Nicholas, Obler, Albert, & Goodglass, 1985), with older adults aged 70 or more performing less accurately and slower than younger adults (MacKay et al., 2002; Nicholas et al., 1985; Tsang & Lee, 2003; see Goral, 2004, for review).

However, many investigations have failed to report significant age differences in naming accuracy (e.g., Béland & Lecours, 1990; Wierenga et al., 2008), while some studies have reported even higher naming accuracy by older adults (e.g., Schmitter-Edgecombe, Vesneski, & Jones, 2000). According to a past review of 25 investigations (Goulet, Ska, & Kahn, 1994), differences between younger and older adults usually appertain to naming speed and not to naming accuracy. According to data from young individuals, executive control abilities of inhibition and updating contribute to individual differences in the speed of naming objects and actions (Shao, Roelofs, & Meyer, 2012). Evidence suggests that slowed processing speed may modulate age-related difficulties in naming abilities (e.g., Facal, Juncos-Rabadán, Rodríguez, & Pereiro, 2012), which may be related to the age-related over-recruitment of frontal brain regions associated with cognitive control (Wierenga et al., 2008).

Several results from studies examining retrieval for different semantic / grammatical classes of words, indicate a dissociation between action and object naming. More specifically, action naming seems to be better preserved than object naming in the healthy ageing population (e.g., Barresi et al., 2000; Nicholas et al., 1985). Results from lesion studies have also indicated that damage in frontal areas of the left hemisphere predominantly affects action naming while damage in the left temporal lobe disrupts object naming (e.g., Daniele et al., 1994; Shapiro & Caramazza, 2003; see Gainotti, Silveri, Daniel, & Giustolisi, 1995, for review). A large study involving patients with unilateral lesions by Tranel and colleagues (2001), however, suggested that frontal damage leads to deficits in both action and object naming, while temporal lesions affect object but not action naming. In line with this, several neuroimaging studies have revealed similar neural activations during object and action naming (e.g., Saccuman et al., 2006; Tyler, Russell, Fadili, & Moss, 2001), involving the left dorsolateral prefrontal cortex (e.g., Hernandez, Dapretto, Mazziotta, & Bookheimer, 2000), as well as the fusiform gyrus and anterior cingulate (Garn, Allen, & Larsen, 2009). Similarly, lesion studies have shown that the disruption of fronto-temporal connections may result in impaired lexical retrieval of both object and action names (Lu et al., 2002), confirming that there are overlapping neural substrates for lexical retrieval of distinct classes of words. The findings above suggest that conceptual knowledge is represented within a wide non-differentiated neural system (Tyler et al., 2001), however, it has been shown that distinct semantic dimensions (and not grammatical classes) may be underpinned by different neural substrates. For example, Saccuman and colleagues (2006) reported that retrieval of words (either verbs or nouns) that involve manipulation of properties is associated with increased activation of fronto-parietal networks, which support hand-action representations, in the absence of general differences due to grammatical class.

Over the last two decades, there has been an increasing interest in naming abilities for spatial relations, which requires retrieval of spatial prepositions (e.g., *in*, *around*, *close*, etc.). In a PET study by Damasio and colleagues (2001), both naming actions and spatial relations was associated with activations in the left dorsolateral prefrontal cortex, as well as in the left inferotemporal cortex. However, spatial naming was also related to increased bilateral activity in parietal regions, especially in the right hemisphere for relations between abstract stimuli and in the left for naming spatial relations between concrete objects (Damasio et al., 2001). Results from fMRI investigations also showed increased activity in the inferior parietal cortex and frontal areas during processing of spatial relations (Amorapanth et al., 2010). Meanwhile, a number of patient studies has revealed that lesions affecting the left prefrontal and inferior parietal opercula result in impaired processing of locative prepositions (Kemmerer & Tranel, 2003; Tranel & Kemmerer, 2004; Wu, Waller, & Chatterjee, 2007), and that the retrieval of words describing static or dynamic spatial relations between concrete objects is hampered after frontal or parietotemporal damage (Göksun et al., 2013). Nevertheless, spatial naming abilities have not been previously investigated in typically and atypically ageing populations.

Summary. Many linguistic skills, including language comprehension and semantic knowledge, remain well preserved in normal ageing or even improve across the lifespan, while learning novel verbal information declines with increasing age. On the other hand, there are mixed and inconclusive results regarding the ageing effects on different aspects of language production. Overall, there seem to be some mild deficits in language production amongst older individuals, which are usually attributed to impaired strategical control processes underpinned by frontal brain regions.

4.2.3 Visuospatial abilities in ageing

Visuospatial abilities form a multifaceted aspect of cognition that enables an organism to encode, represent, organize, analyse, understand, manipulate, maintain, and remember spatial information in the environment, as well as to physically navigate in the environment, and communicate these information to others (Burgess, 2008; Hegarty & Waller, 2005; Spence and Feng, 2010; Wolbers & Hegarty, 2010). It is important to note that visuospatial abilities may be examined within different scales of space, including figural, vista, environmental, and geographical space (Montello, 1993). Figural space is small in scale relative to the body of the perceiver, can be apprehended from a single viewpoint, and it includes pictorial figures and manipulable three-dimensional objects. The scale of vista space is medium sized, as it is larger relative to the body of the perceiver, but can be apprehended from a single viewpoint, and it includes single rooms, town squares, and horizons. Environmental space is larger in scale relative to the body and it typically requires locomotion for its apprehension, as it includes spaces of entire buildings, neighbourhoods, or cities. Geographical space is projectively much larger than the body and requires symbolic representations for its apprehension (reducing it to figural space), as it includes countries and the solar system (Montello, 1993).

Small-scale visuospatial cognition can be examined with pencil-and-paper tests assessing abilities of perception and integration (the ability to understand visual representations and their spatial relationships), mental imagery (the ability to mentally represent and manipulate spatial information, including mental rotation of objects or the self), memory, and verbal production and comprehension of spatial relations between pictorial and three-dimensional objects and people. On the other hand, larger-scale visuospatial tasks examine learning and memory of new environments, navigating in the environment, including way-finding (when a route is followed to a familiar location), route-learning (when a route is learned to a novel location) and locating an object which cannot be seen directly (Hegarty, Montello, Richards, Ishikawa, & Lovelace, 2006; Moffat, 2009), as well as production and comprehension of verbal navigation directions. Moreover, visuospatial processing at any scale may involve representations within different spatial reference frames, i.e., coordinate axial systems relative to which spatial locations are defined (Burgess, 2006; Carlson, 1999; Levinson, 1996, 2003; Montello, 1993; see Section 2.2). These coordinate systems include the self-centred (relative) frame, and the allocentric object-centred (intrinsic) and environment-centred (absolute) frames of reference (Burgess, 2006; Levinson, 1996, 2003).

Small-scale visuospatial abilities. Several studies have examined the effects of ageing on visuospatial abilities, and, despite the variation in aspects of visuospatial processing examined, most results indicate significant declines among older individuals (for reviews, see Iachini et al., 2009; Klencklen, Després, & Dufour, 2012; Lithfous, Dufour, & Després, 2013; Moffat, 2009). More particularly, older adults exhibit decreased speed of processing visuospatial information (e.g., Jenkins, Myerson, Joerding, & Hale, 2000; Meadmore, Dror, & Bucks, 2008). In addition, ageing has a detrimental effect on visuospatial working memory abilities (Alichniewicz, Brunner, Klünemann, & Greenlee, 2012; Bo, Borza, & Seider, 2009;

Cornoldo, Bassani, Berto, & Mammarella, 2007; Jenkins et al., 2000; Park et al., 2002; see Sander, Lindenberger, & Werkle-Bergner, 2012, for a review), including visuospatial working memory updating, i.e., the ability to selectively update relevant information and suppress no-longer-relevant information (Fiore, Borella, Mammarella, & De Beni, 2012), and spatial paired-association learning (Jenkins et al., 2000). Older adults may also perform poorly in visuospatial working memory tasks that require generation and manipulation of mental images (mental imagery) and manipulation of the level of activation of information in a given memory content (Fiore, Borella, Mammarella, & Cornoldi, 2011). The age-related declines in visuospatial working memory abilities seem to be widespread, as they have been observed across simple visual storage tasks, as well as spatial-sequential and spatial-simultaneous tasks (Mammarella, Borella, Pastore, & Pazzaglia, 2013).

These findings are consistent with the notion of a less efficient top-down updating and inhibitory control over visuospatial working memory contents (Sander et al., 2012). Findings regarding visuospatial attention in older adults, however, indicate a dissimilar pattern. According to several investigations, older adults perform equally with younger adults on visuospatial attention tasks, including tasks of voluntary spatial attention shifts (Greenwood, Parasuraman, & Haxby, 1993), even under conditions of significant cognitive load (Thornton & Raz, 2006). Furthermore, some studies found no age differences in visual attention accuracy examined by visual search tasks, despite higher reaction times for older adults and altered neural activation patterns compared to younger adults, such as increased bilateral frontal activity coupled with reduced occipital activity (Cabeza et al., 2004; Madden et al., 2007). Neurophysiological investigations have also reported age-related differences in neural activity during visuospatial attention paradigms, as well as slower encoding yet intact attentional modulation of visuospatial information in older adults (e.g., Störmer et al., 2013; Wiegand et al., 2014). In sum, despite the overall slowing of perceptual processing speed, there is evidence suggesting efficient visual search with increased age (see Madden, 2007, for a review).

Ageing effects on visuospatial abilities have been reported in several studies comparing a group of older and a group of younger adults (e.g., Jenkins et al., 2000). However, few cross-sectional or longitudinal studies have examined higher-order visuospatial information processing and organization abilities (also called spatial visualization), which require multistep mental manipulations of complex stimuli (Salthouse, Babcock, Skovronek, Mitchell, & Palmon, 1990). Cross-sectional studies have associated increased age with lower performance in visuospatial organization tasks (e.g., Giannakou & Kosmidis, 2006; Hooper, 1983), with a more prominent decline from the mid-50s (e.g., Borella, Meneghetti, Ronconi, & De Beni, 2014) or mid-60s (e.g., Hoogendam, Hofman, van der Geest, van der Lugt, & Ikram, 2014). Moreover, it has been shown that older adults exhibit difficulties in visuospatial reasoning during tasks that require complex relational integration processing (Viskontas, Holyoak, & Knowlton, 2005) even at a medium level of relational complexity (Viskontas, Morrison, Holyoak, Hummel, & Knowlton, 2004).

Similarly, cross-sectional studies have associated increased age with poorer mental imagery abilities assessed by tasks of mental rotation of figures or objects (Borella et al., 2014; Devlin & Wilson, 2010; Hertzog & Rypma, 1991; Inagaki et al., 2002; Jansen & Heil, 2009; Salthouse et al., 1990). Age-related declines in object-based mental rotation tasks have been attributed to spatial working memory impairments (Hertzog & Rypma, 1991), however, Kemps and Newson (2005) found that object mental imagery abilities depend primarily on processing speed and sensorimotor functioning, with trivial contributions from working memory and executive functions. Spatial perspective taking (also called spatial orientation), which refers to the ability to imagine spatial relations from another perspective (Zacks, Mires, Tversky, & Hazeltine, 2002), has been less thoroughly investigated in older adults. Psychometric results have revealed that perspective transformations are dissociable from object mental rotation abilities (Hegarty & Waller, 2004; Kozhevnikov & Hegarty, 2001), since it involves self-based mental rotations rather than object-based mental rotations (Kessler & Thomson, 2010; Kessler & Rutherford, 2010; see Zacks & Michelon, 2005 for a review). Moreover, these two spatial transformation abilities are characterized by different neural correlates, with object-based mental rotations being primarily supported by occipito-parietal regions, mainly in the right hemisphere, while left-lateralized dorsal stream components of the posterior cortex along with lateral frontal areas seem to be critical for perspective transformations (Zacks, Vettel, & Michelon, 2003; see Zacks, 2008, for a meta-analysis and review).

Using Kozhevnikov and Hegarty’s (2001) object-perspective taking task (OPT), a task in which people are shown a two-dimensional array of objects, imagine taking a perspective within the array, and point to the direction to a third object from the imagined perspective, Zancada-Menedez et al. (2016) found older adults performing worse than middle-aged and younger adults in spatial perspective taking, while middle-aged adults also performed worse than younger adults. Similarly, using a variant of Piaget’s three-mountain task that required participants to imagine how an array of real objects would be from a different viewpoint and reconstruct it using blocks, Inagaki et al. (2002) reported impaired perspective taking abilities in older adults compared to middle-aged and younger adults. Using the OPT in a larger cross-sectional study, Borella and colleagues (2014) found an age-related decline in spatial perspective taking, which was apparent from the age of 50 years onwards.

Increased age has also been associated with poor episodic memory for visuospatial information in numerous investigations (see Iachini et al., 2009, for a review). Episodic visuospatial memory is usually examined with complex figure tests, such as the Rey-Osterrieth complex figure test (ROCF; Rey, 1953), in which participants are shown a complex figure and after copying it they are required to reproduce it from memory immediately and after a short delay. Several normative and cross-sectional studies have repeatedly pointed to an age-dependent decline in episodic memory for visuospatial information assessed by complex figure tests (e.g., Caffarra, Vezzadini, Dieci, Zonato, & Venneri, 2002; Fastenau, Denburg, & Hufford, 1999; Luzzi et al., 2011; Park et al., 2002; Peña-Casanova et al., 2009). Highlighting the role of the hippocampus on visuospatial memory abilities even within figural space, using the ROCF in a cross-sectional study, Carlesimo and colleagues (2010) found that high hippocampal diffusivity in older individuals was a significant predictor of the decline in delayed visuospatial recollection. Age effects in visuospatial episodic memory within manipulable space are more pronounced for egocentric compared to allocentric representations (e.g., Ruggiero, D'Errico, & Iachini, 2016).

Large-scale visuospatial abilities. Age effects on spatial abilities have been extensively studied in rodents. Impaired spatial learning and memory (as examined by maze tasks and recognition of novel locations in a familiar environment) is already apparent in middle-aged rodents (e.g., Luine, Wallace, & Frankfurt, 2011), while little or no age-related impairments are observed in the acquisition of motor or procedural skills (e.g., Cassel et al., 2007). The early onset and distinctive decline of spatial memory suggests that the neural systems supporting spatial abilities are substantially susceptible to ageing. It is well accepted that the hippocampus is critical for spatial processing (Burgess, 2008) and past research has shown that hippocampal damage results in distinct impairments in learning and memory for spatial locations, while object memory is well preserved (e.g., Tata, Markostamou, Ioannidis, Simeonidou, & Spandou, 2015). Indeed, progressive decline in large-scale spatial memory during ageing has been associated with decreased hippocampal volume both in rodents (e.g., Driscoll et al., 2006) as well as in humans (e.g., Head & Isom, 2010; Reuter-Lorenz & Park, 2010).

Meanwhile, there has been an increasing interest in investigating ageing effects on large-scale spatial abilities in humans (see Lithfous, Dufour, & Després, 2012; Moffat, 2009, for reviews), with the use of virtual environments as well as real-world settings. Using a real-world Morris water maze analogue for humans, Newman and Kaszniak (2000) reported impaired allocentric spatial memory in older adults compared to younger individuals. In a more recent study that involved a real-world analogue of the Morris water maze by Gazova et al. (2013), older adults performed poorer than younger adults in an allocentric spatial learning task that required memory for spatial relations between a hidden location and two distal cues, while there were no age differences in an egocentric spatial learning task that required finding the hidden location from a fixed start position. Moreover, older individuals are slower and make more turning errors than younger adults during navigation in novel real-world environments with the use of a map (Wilkniss et al., 1997), suggesting a difficulty in transferring survey knowledge to route-learning.

Within the last few decades, age-related impairments in navigation abilities, including route learning and memory, have been reported in many studies that employed virtual environments (e.g., Driscoll et al., 2005; Iaria et al., 2009; Moffat et al., 2001; Moffat & Resnick, 2002; for a review see Moffat, 2009). For example, using a virtual maze route-learning task, Moffat, Zonderman, and Resnick (2001) found that younger adults were faster and more efficient in locating the goal location compared to middle-aged and older adults, while middle-aged adults performed faster but committed similar amounts of errors compared to older adults. Moreover, Yamamoto and DeGirolamo (2012) investigated age differences in spatial memory through exploratory navigation (route-based learning) or from a map-like aerial perspective (survey-based learning). They found that older adults performed equivalently with younger adults in survey-based spatial learning, but were exhibited poorer memory through route-learning, suggesting that navigation abilities are more vulnerable to ageing effects than map reading skills (Yamamoto & DeGirolamo, 2012).

Some studies have focused on possible discrepancies between egocentric- and allocentric-based spatial memory in ageing (e.g., Driscoll et al., 2005; Moffat et al., 2007; Wiener, Kmecova, & de Condappa, 2012; Yan, Daugherty, & Raz, 2014). For example, Wiener et al. (2012) examined the effects of ageing on route repetition and route retracing (navigating from the end of a route back to the start location) in virtual environments, and found that older adults performed equally with the young adults on route repetition that relied on egocentric processing, but significantly worse on route retracing, which, in contrast, was supported by allocentric processing. Similarly, Rodgers, Sindone, and Moffat (2012) investigated age differences in preferences of navigation strategies using a virtual Y-maze. Older adults clearly preferred egocentric strategies, whereas younger adults' preferences were equally spread between egocentric and allocentric. Based on this finding, researchers suggested that this egocentric (in contrast to an allocentric) strategy preference among older adults may affect navigational abilities. Another study by Harris, Wiener, and Wolbers (2012) investigated age-related changes in navigational abilities using a virtual plus maze. More particularly, they assessed participants' ability to use allocentric and egocentric strategies, as well as their ability to switch between strategies. According to their findings, older adults exhibited impaired use of allocentric but not egocentric strategies. Further analyses revealed that older adults performed worse when they actually had to switch strategies from an egocentric to an allocentric one rather than employing allocentric strategies per se, which led the researchers to argue that this specific switching deficit may account for the apparent age-related impairment in navigational abilities (Harris et al., 2012). Results from another investigation by Wiener, de Condappa, Harris, and Wolbers (2013) also revealed that older participants exhibit a persistent preference for egocentric (response) strategies coupled with a failure to use appropriate allocentric (space) strategies when required for successful navigation. Interestingly, Begega and colleagues (2001) found that older rats perform poorly in spatial learning and memory tasks when using allocentric cues (i.e., Morris water maze) but not when using egocentric cues (i.e., T water maze), supporting that the effect of age in spatial abilities depends on the strategies required and the reference frame (allocentric vs egocentric) to accomplish a particular task.

Several studies have also examined age differences on path integration, which refers to the ability to way-find with motion-based information by integrating vestibular, proprioceptive, and visual sensory feedback in the absence of environmental cues (Mahmood, Adamo, Briceno, & Moffat, 2009). Path integration is usually assessed using return-to-origin tasks (the so-called "triangle completion tasks"), where participants attempt to return to the point of origin after having moved along two segments of a triangular path. So, for a successful triangle completion the individual has to integrate different spatial components simultaneously, including angular rotations and distances travelled (Adamo et al., 2012). It is believed that effective path integration depends on response strategies based on stimulus-response associations rather than spatial (i.e., allocentric) strategies that are based on external landmarks of the environment (Konishi & Bohbot, 2013). Spatial responses are considered to rely heavily on the hippocampus whereas "response strategies" are largely associated with parietal areas and dorsal striatum regions (especially the caudate nucleus) (Doeller, King, & Burgess, 2008; Etchamendy & Bohbot, 2007; Packard & McGaugh, 1996). Using virtual environments, Mahmood and colleagues (2009) found that ageing has a negative effect on visual path integration due to impairments in estimating rotations and distances simultaneously. Harris and Wolbers (2012) investigated visual path integration in virtual environments with and without landmark information, and found that older participants were less accurate in reproducing long distances and larger turns compared to younger adults, and that they performed worse in triangle completion tasks, even with additional landmark information. In a recent study, Adamo et al (2012) investigated age-related differences in distance reproduction and triangle completion tasks in virtual environments as well as in two real-world settings that involved active (guided walking) or passive movement (via wheelchair propulsion). While there were no age differences in distance reproduction tasks, older individuals performed worse in triangle completion tasks when vestibular information or optic flow were the only source of self-motion information, suggesting that older adults may require the integration of several sources of sensorimotor information for successful path integration than younger adults. Furthermore, these results stress that apart from visual sensory information, vestibular and proprioceptive sensory feedback also contribute to successful navigation (Adamo et al., 2012). In fact, older adults may also show deficits in non-visual (vestibular) path integration tasks (Allen et al., 2008). To summarize, the studies described above are indicative of impaired route-based navigation abilities in older adults.

Summary. Taken together, the studies reviewed above have revealed an age-related deterioration of both small- and larger-scale visuospatial abilities. Within small-scale space, these include impairments in the speed of processing visuospatial information (e.g., Meadmore et al., 2008), as well as deficits in visuospatial visualization (Borella et al., 2014; Hoogendam et al., 2014), reasoning (Viskontas et al., 2004, 2007), working memory (e.g., Alichniewicz et al., 2012; Cornoldo et al., 2007; Fiore et al., 2011, 2012; Mammarella et al., 2013), episodic memory (Caffarra et al., 2002; Carlesimo et al., 2010; Luzzi et al., 2011; Park et al., 2002), and mental imagery abilities for both object-based mental rotations and spatial perspective taking (Borella et al., 2014; Inagaki et al., 2002). Moreover, older adults exhibit difficulties in effective and appropriate use of allocentric place strategies during navigation (e.g., Rodgers et al., 2012), which may be associated with switching costs in tasks that require alternating between egocentric and allocentric strategies (Wiener et al., 2013). However, older adults exhibit a generalized deficit in the acquisition of allocentric knowledge (Antonova et al., 2008; Gazova et al., 2013; Iaria et al., 2009; Newman & Kaszniak, 2000). Nevertheless, there is substantial evidence indicating deficits in route-learning through egocentric response strategies with increased age (Adamo et al., 2012; Harris and Wolbers, 2012; Mahmood et al., 2009). It is noteworthy that spatial abilities at different scales may be partially dissociated, however, there is evidence supporting a significant degree of overlap between small- and large-scale visuospatial cognition (Hegarty et al., 2006). In line with this, large-scale navigation abilities have been highly correlated with measures of mental rotation and visual memory for figures in ageing studies (Moffat et al., 2001).

The aforementioned age-related changes in visuospatial cognition may be mediated by structural and functional changes of the brain affecting frontal, parietal, hippocampal and striatal circuits (Jagust, 2013). Several studies have revealed that egocentric spatial processing (including the use of response strategies in route-learning navigation paradigms) is thought to rely on parietal and striatal circuits, mainly in the caudate nucleus, whereas visuospatial memory (e.g., Hartley et al., 2007; Hartley & Harlow, 2012) and allocentric spatial processing (including the use of space strategies during navigation) relies on hippocampus (e.g., Bird & Burgess, 2008; Doeller et al., 2008; Etchamendy & Bohbot, 2007; Head & Isom, 2010; Iaria et al., 2003; Konishi & Bohbot, 2013; Reuter-Lorenz & Park, 2010). Age-related deficits in visuospatial memory and allocentric processing may reflect an age-dependent functional and structural hippocampal degeneration (e.g., Antonova et al., 2009; Apostolova et al., 2012; Moffat et al., 2006), as past research has shown that the hippocampal formation is particularly vulnerable to the damaging effects of ageing (Grady, 2008; Rosenzweig & Barnes, 2003).

4.3 Conclusions

Ageing is a continuous process which does not begin at a particular point in time, however, it affects different functions at different points in time to different extents. Decades of neuropsychological research on ageing has mapped contrasting patterns of decline and stability in cognition across the adult lifespan. Overall, it seems that crystalized abilities are well maintained across the lifespan while fluid abilities that rely on control processes decline (Craik & Bialystok, 2006; see Figure 9). More specifically, both cross-sectional and longitudinal studies have found robust declines in abilities such as processing speed (Borghesani, et al., 2013; Salthouse, 1996), executive processes (West, 1996; Zelazo et al., 2004), small-scale visuospatial processing (Borella et al., 2014; Viskontas et al., 2004; Zancada-Menedez et al., 2016) and large-scale visuospatial abilities (Gazova et al., 2013; Rodgers et al., 2012; Yamamoto & DeGirolamo, 2012), as well as learning novel episodic information (Luo & Craik, 2008). By contrast, language abilities and semantic knowledge, emotional processing, and several aspects of memory, such as short-term memory, autobiographical memory, and implicit memory remain relatively stable (Shafto & Tyler, 2014; Rabbitt et al., 2004; Robbins et al., 1998).

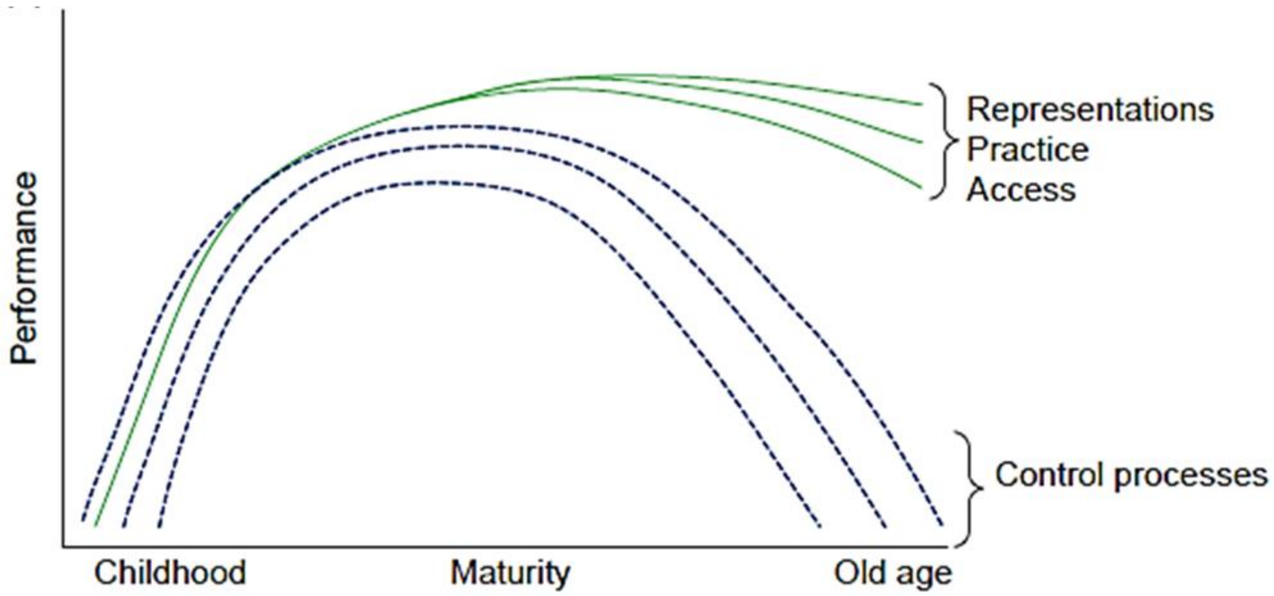


Figure 9. Representations and control processes across the lifespan. Representations are generally well maintained at older ages, but some knowledge is either lost (especially with lack of practice) or becomes inaccessible. Control processes develop at different ages and also decline differentially, depending in part on the brain areas involved (adapted from Craik & Bialystok, 2006).

These contrasts indicate that ageing influences certain cognitive functions disproportionately. Lifespan investigations bearing in mind individual differences can provide valuable information about the nature of different cognitive systems and their neural underpinnings. Moreover, identifying the adult lifespan trajectories of different aspects of cognition may help us discriminate healthy from pathological ageing. The next chapter presents novel findings from a large sample of healthy individuals, focusing on the adult lifespan trajectories of spatial language abilities and contrasting them to the trajectories of linguistic and visuospatial abilities.

Chapter 5 Spatial language and cognition across the adult lifespan (2nd series of studies)

5.1 Objectives and hypotheses

As the life expectancy of the world population increases, a better understanding of the ageing effects on cognition is necessary. As discussed in Chapter 4, increasing age has been associated with declines in control abilities and processing resources (Jurado & Rosselli, 2007; Salthouse, 2006; West, 1996; Zelazo et al., 2004), as well as with impairments in several aspects of visuospatial cognition (Borella et al., 2014; Klencklen et al., 2012; Lithfous et al., 2012). On the other hand, crystalized and language abilities seem to remain intact across the adult lifespan (Craik & Bialystok, 2006).

Meanwhile, the impact of ageing on different aspects of spatial language processing is largely unexplored. Nevertheless, our ability to communicate spatial relations with verbal means is fundamental to everyday functioning and constitutes a core part of human linguistic communication. Therefore, the main objective of the present studies was to investigate age-related effects on various spatial language abilities from an adult-lifespan perspective for the first time. More specifically, we used the newly-developed spatial language tasks (see Chapter 3) in order to investigate cued-word production for spatial terms (Spatial Verbal Fluency task), naming abilities for depicted static and dynamic spatial relations (Spatial Naming Test), episodic verbal memory for spatial information presented from a route or a survey perspective (Spatial Verbal Memory task), as well as verbal comprehension for descriptions of static spatial relations under different reference frames, including self-centred and third-person-centred, object-centred, and environment-centred reference frames (Verbal Comprehension in Spatial Reference Frames task). The cross-sectional design applied in the current studies allowed analyses of the complete adult age continuum instead of comparisons between only two extreme groups. Of particular interest was to examine the onset of potential age-related changes in spatial language abilities and to establish whether these changes are linear or accelerate in later life.

Furthermore, we examined the adult lifespan trajectories of analogous (non-spatial) verbal abilities (including semantic and phonemic verbal fluency, object and action naming, episodic verbal memory, and vocabulary knowledge) and various (non-verbal) visuospatial abilities (including visuospatial organization, reasoning, and episodic memory, as well as mental rotation, and object-perspective taking), as well as abilities of cognitive control and processing resources (including mental flexibility, inhibition, short-term and working memory, and speed of processing verbal and visuospatial information). This individual differences approach allowed complete age trends to be contrasted across the novel spatial language measures and diverse cognitive tasks, and thus to identify which processes are most vulnerable to ageing effects.

As discussed in Chapter 2, spatial language forms a unique semantic category lying between language and perception as it requires effective coordination between linguistic and perceptual processes onto a mental representation of space (Carlson-Radvansky & Irwin, 1993). There is substantial evidence supporting a close relationship between spatial semantics and non-linguistic spatial cognition (e.g., Chatterjee, 2001; Coventry et al., 2014; Hayward & Tarr, 1995; Munnich et al., 2001; Noordzij et al., 2008). Therefore, besides age-related impairments in visuospatial cognition, we expected to see significant age effects on spatial language processing, with a more attenuated decrease in performance during the later years of life. At the same time, we expected to find mild or no age effects on non-spatial verbal abilities. Moreover, we anticipated that the age effects would be more pronounced in those aspects of spatial language processing that are highly correlated with visuospatial abilities. An age-related decrease in speed of performance was also expected in those tasks in which time of completion was recorded.

Mental representations of space are contextualised within different coordinate systems (reference frames, RF) that can be person-centred (relative RF), object-centred (intrinsic RF), or environment-centred (absolute RF) (Carlson, 1999; Levinson, 1996; Klatzky, 1998; see Section 2.2). Past research has shown that older adults may exhibit difficulties in both egocentric- and allocentric-based visuospatial processing (Harris & Wolbers, 2012; Wiener et al., 2012; Wilkniss et al., 1997), however, taking into account that allocentric processing requires additional coordination processes, we expected that performance in tasks requiring allocentric processing, as in the absolute (environment-centred) condition of the VCSRF, would be more challenging for older adults.

After having established the test-retest reliability of the novel spatial language tasks (see Section 3.4), another important aim of the present studies was to further examine their psychometric properties and their concurrent and construct validity. Subsequently, we determined how performance on each spatial language task relates to performance on their analogous non-visuospatial verbal tasks and to performance on non-verbal visuospatial tasks through factorial classification and a series of hypothesis-driven correlational analyses. A complementary aspect we investigated was whether the relationship between performance on spatial language tasks and performance on different cognitive tasks remains stable or changes across the adult lifespan.

We also examined whether performance on the novel spatial language tasks is influenced by demographic factors such as education and gender, apart from age, and produced adjusted normative data for the English population. We expected that higher levels of education would be associated with better cognitive performance. Whether there are gender differences in spatial language production, memory, and comprehension under different spatial reference frames is an issue that also needs to be addressed, since these abilities have not been examined in adults. Nonetheless, given the influence of gender on visuospatial abilities, with males outperforming females (Hegarty & Waller, 2005), gender effects could also emerge in spatial language abilities.

In conclusion, the present studies will help us identify for the first time the typical adult lifespan trajectories of possible decline in different aspects of spatial language processing, and whether these trajectories map onto the trajectories of non-verbal visuospatial and non-visuospatial verbal abilities. Moreover, the current investigations will help us establish the validity of the novel spatial language tasks, that could subsequently be used in future experimental paradigms as well as in clinical settings with patient populations.

5.2 Methods

5.2.1 Participants

Data included in the present studies were obtained from a randomly selected sample of 160 individuals, who were recruited from East Anglia regions of the UK, including Norwich and Norfolk, Suffolk, and Cambridgeshire, through advertisements in local media, invitation leaflets, and word of mouth. Participants were selected in order to cover an age range spanning from 18 to 85 years, and to form five groups classified by 10-year age brackets (age groups: 18-28, 45-54, 55-64, 65-74, 75-85 years; N = 30 to 34 per age group). In each age bracket of individuals aged between 45 to 85, participants were further classified by age in half-decades to achieve optimum age distributions for each age group in our sample (i.e., 45-49, 50-54, 55-59, 60-64, 65-69, 70-74, 75-79, 80-85 years; N = 15 to 16 per age subgroup). Moreover, participants' selection followed a balanced representation of sexes in each half-decade age group. Demographic information collected from all participants included age, gender, hand preference, years of formal education, as well as a detailed medical history.

Medical history included any past or present diagnosis of any neurological conditions (e.g., epilepsy, multiple sclerosis, etc.), stroke or traumatic brain injury, mood or psychiatric disorders, learning disabilities, or any other medical condition, including cardiovascular diseases and endocrinological disorders, such as diabetes. Participants also reported vision and hearing loss, substance use and the average amount of alcohol units they consumed in a week, as well as any prescribed medication being taken. Participants' characteristics within each age group are presented in Table 7.

Participants who did not speak English as their first language or had been diagnosed with a condition that could affect cognitive functioning were excluded from the study. A score lower than 25 points in the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005) also resulted in exclusion from the study. Substance abuse was an additional exclusion criterion, as it can lead to cognitive impairment (Vik, Cellucci, Jarchow, & Hedt, 2004). All participants had normal vision and hearing or corrected to normal with external aids (i.e., spectacles and/or hearing aids). The initial sample included 164 participants, four of whom were excluded from the studies for not meeting all of the criteria described above.

The ratio of male to female participants was comparable across the age groups, $F(4, 155) = .64$, $p > .250$, partial $\eta^2 = .01$. However, there was a significant effect of age group on years of formal education, $F(4, 155) = 7.35$, $p < .001$, partial $\eta^2 = .16$, with participants aged 45-64 having a higher level of education compared to individuals aged 75-85, while participants aged 45-54 also had more years of formal education than those aged 65-74. Anxiety and depressive mood[1] were highest in young adulthood and decreased linearly across the lifespan [effect of age group on anxiety score: $F(4, 155) = 8.85$, $p < .001$, partial $\eta^2 = .18$; effect of age group on depressive mood: $F(4, 155) = 7.90$, $p < .001$, partial $\eta^2 = .17$], supporting the notion that ageing is generally associated with better emotional well-being (Carstensen et al., 2011; Charles, 2010) and an intrinsic reduction in susceptibility to anxiety and depression (e.g., Henderson et al., 1998; for a review, see Jorm, 2000). On the other hand, vision and hearing loss increased with age, particularly after the mid-50s. Similarly, the number of prescribed medications also increased with age as one would expect, especially from the mid-50s onwards. The most frequent causes for taking prescribed medications were hypertension and high cholesterol, followed by arthritis, asthma, arrhythmia and other

[1] We used the GAD-7 (Generalized Anxiety Disorder 7; Spintzer, Kroenke, Williams, & Löwe, 2006), a 21-point self-report scale, as a brief measure of generalized anxiety, and the PHQ-9 (Patient Health Questionnaire 9; Kroenke, Spintzer, & Williams, 2001), a 27-point self-report scale, as a brief measure of depression severity.

cardiovascular conditions, diabetes, gastro-oesophageal reflux disease, glaucoma, osteoporosis, incontinence, thyroid disorders, and for hormone replacement therapy.

5.2.2 General procedure

All participants participated voluntarily, provided written informed consent for the participation, and received a monetary compensation of £14 for their time and efforts. About two thirds of the participants in the 18-28 age group received course credits for their participation. Testing took place in a quiet room at the School of Psychology of the University of East Anglia between 9:00 h – 18:00 h and was performed on an individual (one-to-one) basis in a single session lasting approximately two hours, with breaks taken whenever required.

At the outset of each session, participants completed a semi-structured interview providing detailed health and demographic information, followed by the MoCA administration. Next, they were tested on the newly developed measures assessing spatial language processing (see Chapter 3), as well as on an extended battery of well-established neuropsychological tests assessing different aspects of cognition (see Table 8 for a list of all tasks administered), including visuospatial abilities (i.e., visuospatial short-term, working, and episodic memory; visuospatial organization; mental rotation; visuospatial reasoning; and object-perspective taking) and verbal abilities (including verbal short-term, working, and episodic memory; object and action naming; semantic and phonemic verbal fluency; and vocabulary knowledge), as well as inhibitory control, mental flexibility, and processing speed of verbal and visuospatial information. They were also administered scales for mood and anxiety. All tasks along with their administration procedures and outcome scores are described in the next section (5.2.3). All tasks were presented in a printed format, and were administered in a semi-randomized order.

All experimental procedures were ethically approved by the School of Psychology Ethics Committee in line with the policies of the University of East Anglia Research Ethics Committee and the British Psychological Society guidelines.

Table 7. *Participants' Characteristics (Means and Standard Deviations) by Age Group*

	Age group (years)					
	18-28	45-54	55-64	65-74	75-85	Total
N	34	30	32	32	32	160
Age (years)	20.8 (2.19)	49.80 (3.26)	59.40 (2.57)	69.30 (2.40)	79.46 (2.90)	55.40 (20.6)
Education (years)	13.8 (1.94)	15.80 (3.07)	14.80 (3.52)	13.20 (2.62)	12.10 (3.32)	13.90 (3.16)
Gender (females)	52.0%	68.0%	59.0%	53.0%	62.0%	59.0%
Handedness (right)	94.1%	96.7%	87.5%	90.6%	93.8%	92.5%
General cognitive functioning (MoCA)	-	29.31 (1.05)	27.93 (1.92)	27.75 (1.54)	26.43 (1.50)	27.68 (1.82)
Anxiety (GAD-7)	6.67 (4.63)	3.50 (3.97)	3.62 (3.52)	2.34 (2.79)	2.00 (2.51)	3.67 (3.91)
Depressive mood (PHQ-9)	6.00 (4.43)	3.33 (4.04)	3.15 (3.93)	2.18 (2.45)	1.59 (1.64)	3.28 (3.76)
Medications (number)	0.03 (0.17)	0.43 (0.62)	1.12 (1.43)	1.46 (1.50)	1.78 (1.56)	0.83 (1.25)
Vision loss	17.6%	26.7%	62.5%	59.4%	62.5%	45.6%
Hearing loss	2.9%	10.0%	25.0%	15.6%	21.9%	15.0%

Note. Values represent means (and standard deviations). MoCA = Montreal Cognitive Assessment (Nasreddine et al., 2005), a 30-point scale used as a brief measure of general cognitive functioning; PHQ-9 = Patient Health Questionnaire 9 (Kroenke et al., 2001), a 27-point self-report scale used as a brief measure of depression severity; GAD-7 = Generalized Anxiety Disorder 7 (Spintzer et al., 2006), a 21-point self-report scale used as a brief measure of generalized anxiety.

Table 8. List of all Tasks (and Associated Measures)

Verbal fluency (cued word production): Verbal Fluency Task (VFT; Strauss et al., 2006)
- Spatial verbal fluency: **Spatial Verbal Fluency task (SVF)**
- Semantic verbal fluency: “animals”, “actions”
- Phonemic verbal fluency: “F”, “A”, “S”

Naming (lexical retrieval)
- Spatial naming: **Spatial Naming Test (SNT)**
  - **Static Spatial Naming (SNT-S)**
  - **Dynamic Spatial Naming (SNT-D)**
- Object naming: Boston Naming Test (BNT; Kaplan, Goodglass, & Weintraub, 2001)
- Action naming: Action Naming Test (ANT; Obler & Albert, 1979)

Episodic memory
- Spatial verbal memory: **Spatial Verbal Memory task (SVM)**
  - **Spatial verbal memory for route descriptions (SVM-R)**
  - **Spatial verbal memory for survey descriptions (SVM-S)**
- (Non-spatial) Verbal memory: Logical Memory subscale (LM; Wechsler, 2010)
- (Non-verbal) Visuospatial memory: Rey-Osterrieth Complex Figure (ROCF; Strauss et al., 2006)

Verbal comprehension in spatial reference frames
- **Verbal Comprehension in Spatial Reference Frames task (VCSRF)**
  - **Self-centred**
  - **Third-person-centred**
  - **Object-centred**
  - **Environment-centred**

Visuospatial processing
- Mental rotation: Mental Rotation Task (MRT; Shepard & Metzler, 1971)
- Visuospatial reasoning: Matrix Reasoning (MR; Wechsler, 2010)
- Visual organization: Hooper Visual Organization Test (HVOT; Hooper, 1983)
- Object-based perspective taking: Object-Perspective Taking test (OPT; Hegarty & Waller, 2004)

Processing speed
- Verbal processing speed: Stroop Task – Names (ST-N; Golden, 1976)
- Visual processing speed: Stroop Task – Colours (ST-C; Golden, 1976)

Short-term and working memory
- Verbal short-term memory: Digit Span – Forward (DS-F; Wechsler, 2010)
- Verbal working memory: Digit Span – Backward (DS-B; Wechsler, 2010)
- Visual short-term memory: Matrix Patterns test (MPT; Riby & Orme, 2013)
- Spatial short-term memory: Spatial Span – Forward (SS-F; Wechsler, 2010)
- Spatial working memory: Spatial Span – Backward (SS-B; Wechsler, 2010)

Mental flexibility: Trail Making Test – Part B (TMT-B; Strauss et al., 2006)

Inhibitory control: Stroop Task – Colours-Names (ST-CN; Golden, 1976)

Vocabulary knowledge: Mill Hill Vocabulary Test (MHVT; Raven, 1981).

General cognitive functioning: Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005)

Anxiety: Generalized Anxiety Disorder 7 self-report scale (GAD-7; Spintzer et al., 2006),

Depression: Patient Health Questionnaire 9 self-report scale (PHQ-9; Kroenke et al., 2001)

Note. Novel spatial language tasks are in bold.

5.2.3 Materials

5.2.3.1 Verbal fluency

Verbal fluency tasks require from participants to generate as many different words as possible in 60 sec according to specific semantic and phonemic cues (Strauss et al., 2006). In the present study participants were asked to generate words belonging to each one of the following semantic categories (semantic verbal fluency): animals (e.g., *cat*, *dog*, *lion*, *zebra*, etc.), actions (e.g., *walk*, *cook*, *listen*, *laugh*, etc.), and words denoting locations (e.g., *inside*, *left*, *between*, etc.; see Section 3.2.1 for a detailed description of the Spatial Verbal Fluency task). On the phonemic trials, participants were asked to generate as many different words as possible beginning with each one of the following letters: "F", "A", and "S". As in standard administration procedures of verbal fluency tasks (Kosmidis et al, 2004; Strauss et al., 2006), participants were instructed to begin generating words orally as soon as they were informed of the category or letter, to avoid repetitions and variations of the same word, and to avoid proper names in the phonemic conditions (e.g., *France*, *Alex*, etc.). Participants were not given any guidelines regarding how to organize their word search and production (e.g., clustering and switching strategies) in any of the conditions. Responses in each condition were recorded verbatim with the use of a voice recorder. Performance was based on the total number of correct words generated in each category.

5.2.3.2 Naming

Participants were administered three naming tasks; the Boston Naming Test (BNT; Kaplan et al., 2001) for object naming (with nouns), the Action Naming Test (ANT; Obler and Albert, 1979) for action naming (with verbs), and the novel Spatial Naming Test (SNT; Section 3.2.2) for naming static and dynamic spatial relations (with spatial prepositions).

Object naming (BNT). The BNT (Kaplan et al., 2001) is the most widely used naming test in neuropsychological assessments (Lezak, 2004). It consists of simple line drawings of objects of graded naming difficulty (e.g., *volcano*, *abacus*; Figure A, Appendix). We used the Williams 30-item version of the BNT (Williams, Mack, & Henderson, 1989), which has been found to be equivalent of the original 60-item version in reliability (Graves, Bezeau, Fogarty, & Blair, 2004; Franzen, Haut, Rankin, & Keefover, 1995). Each pictured object was presented one at a time to the participant, who was asked to name it. Correct identification of the object without providing a phonemic cue was scored one point, according to the BNT manual (Kaplan et al., 2001). Consequently, object naming accuracy was calculated for each participant based on the total number of correct responses, while time of completing the task was recorded as an index of naming speed.

Action naming (ANT). The ANT (Obler & Albert, 1979) consists of 55 simple line drawings of actions of graded naming difficulty (e.g., *sleeping*, *racing*; Figure B, Appendix). Participants were shown each picture and were asked to name the action depicted (i.e., what the person in the picture was doing). Correct identification of the action without providing a phonemic cue was scored one point, similar to the BNT scoring procedures (Kaplan et al., 2001). Consequently, action naming accuracy was calculated for each participant based on the total number of correct responses, while time of completing the task was recorded as an index of naming speed.

Spatial naming (SNT). The SNT (see Section 3.2.2) was developed as an analogue of the BNT (Kaplan et al., 2001) in order to assess naming abilities for static (location of an object; Part A, containing 15 test items) and dynamic (change of location of an object; Part B, containing 15 test items) spatial relations from a self-centred perspective. The stimuli of the SNT consist of line drawings of simple geometrical shapes (Figure 2; Table A, Appendix), with a red ball as the located object and an open cube as the reference object (or more cubes when necessary, as in cases of *between*, *in the middle*, *among*). Black balls were also depicted in order to create a set of different spatial relations, in an attempt to elicit the most suitable response for the target spatial relation in a way that is distinguishable from the non-target relations.

After being given one static and one dynamic example at the outset of each part, participants were shown the 30 test items one at a time and asked to describe as accurately as possible the location (Part A) or the change of location (Part B), respectively, of the located object (red ball) in relation to the reference object (cube) in a way that identifies its location uniquely, distinguishing it from the black balls' location. Optimal responses were scored one point, whereas a less accurate but not incorrect response was scored as a half point. Spatial naming accuracy was based on the total score of correct responses, while speed of performance was recorded as the time required to complete each part.

5.2.3.3 Episodic memory

Participants were administered the Rey-Osterrieth Complex Figure task (ROCF; Osterrieth, 1944; Strauss et al., 2006) for the assessment of visuospatial episodic memory, the Logical Memory (LM) subtest from the WMS (Wechsler, 2010) as a measure of verbal episodic memory, and the newly developed Spatial Verbal Memory (SVM) task in order to assess episodic verbal memory for spatial information presented from a route or a survey perspective, respectively (see Section 3.2.3).

Visuospatial memory (ROCF). The Rey-Osterrieth Complex Figure test (ROCF) was developed by Rey in 1941 and standardized by Osterrieth (1944) and is a widely used neuropsychological test for the evaluation of visuospatial memory. The ROCF consists of three test conditions: copy, immediate and delayed recall. Participants are initially presented with a stimulus figure card (Figure C, Appendix) and asked to freehand draw the figure as accurately and fast as possible (copy condition). The stimulus figure card and the subject's copy are exposed for a maximum of 5 min and a minimum of 2½ min. After completion of the copy production, the stimulus card and the copy drawing are taken away, and participants are given another sheet of paper and instructed to draw the figure from memory (immediate recall trial). Then, after a delay of 25-30 min, they are asked to reproduce the figure from memory again (delayed recall trial). Scoring was performed according to the traditional guidelines developed by Osterrieth's (1944) and described in Strauss et al. (2006). In this scoring system, the figure is subcategorized into 18 particular elements, and each of the 18 elements is evaluated according to a two-point scale, resulting in a 32-point scoring scale. Two points were given when an element was placed and reproduced correctly, 1 point when the element was either reproduced incompletely or misplaced, and half point was attributed when the element was both misplaced and reproduced incompletely. Performance was based on the score achieved in the immediate and delayed recall trials, respectively.

Verbal memory (LM). Episodic verbal memory was examined with the LM subtest of the WMS (Wechsler, 2010). In this task, participants were read one short story and were asked to repeat it immediately after hearing it (immediate recall). Participants were encouraged to recall the story as close to the original passage as possible and to use the same words as the original passage if possible. Twenty-five min after the initial presentation, participants were asked to recall all that they could from the story (delayed recall). All participants were given one standard cue indicating the topic of the story if the participant could not remember anything (i.e., *The story was about a woman who was robbed*). All free recall units were recorded with a voice recorder during the immediate and delayed trials. Scoring was based on the standard scoring rules proposed in the WMS manual; each correct unit recalled was scored 1 point. The depended measures were the total number of correct units recalled immediately and after a 25 min delay, respectively.

Spatial-verbal memory (SVM). The SVM task was used to assess episodic memory for spatial descriptions presented from a route or a survey perspective (see Section 3.2.3 for a full description of the task). In this task, as in the LM task, participants heard two stories, one describing a route in an outdoors natural environment (e.g., *When he saw the Blue Lake in front of him, he turned left*) and the other providing survey descriptions of a town's layout (e.g., *The Library is situated in front of the Church and to the right of the Town Hall*). After hearing each story, participants were asked to orally repeat it immediately and after a ~ 25 min delay. Similarly to the administration guidelines of the LM, a standard cue was provided in the delayed trials if the participant had no memory of the story. All free recall units were separately recorded with a voice recorder during the immediate and delayed trials, and each correct unit was scored one point.

5.2.3.4 Verbal comprehension in spatial reference frames

The Verbal Comprehension in Spatial Reference Frames task (VCSRF; see Section 3.2.4) was used to examine verbal comprehension under four different frames of reference: self-centred, third-person-centred, object-centred, and environment-centred frames. The apparatus consisted of a central circular board on which the reference object (a glass or a car in the intrinsic condition) was placed, surrounded by a rotating circular board on which the located object (a ball) was permanently placed. In the third-person-centred relative condition, a Lego mini-figure person, facing the reference object, was placed directly opposite of the participants' location. In the absolute condition, an arrow pointing to the North was placed ~ 4 metres away at an angle of 45 degrees to the right of the participants' position. The rotating board allowed moving the located object into 8 different locations. In each one of the four conditions, participants were asked to judge as true or false 16 different statements describing spatial relations between the located and the reference objects (e.g., *From your perspective, the ball is to the left of the glass* or *The red ball is SW of the glass*). Participants were explicitly given instructions as to which reference frame they should base their judgements in each condition (e.g., in the intrinsic condition: *This time, you should base your judgments with reference to the car's perspective*). The total number of correct responses in each condition was calculated as an index of accuracy of performance, while the time required to complete each condition was recorded as an index of speed of performance.

5.2.3.5 Visuospatial abilities

Visuospatial abilities were assessed using the following tasks: the Hooper Visual Organization Test (HVOT; Hooper, 1983); the Mental Rotation Task (MRT; Shepard &

Metzler, 1971); the Matrix Reasoning (MR; Wechsler, 2010); and the Object-Perspective Taking test (OPT; Hegarty & Waller, 2004). All of these tasks are described in detail below.

Visuospatial organization (HVOT). The HVOT (Hooper, 1983) is a commonly used test of visuospatial integration abilities. It consists of 30 line drawings of common objects that are fragmented into two or more pieces in a puzzle-like fashion, requiring mental rearrangement of the pieces to identify the item (Figure D, Appendix). Administration and scoring followed the guidelines specified in the manual (Hooper, 1983). Each picture of the disassembled items was presented one at time, and the participant was asked to identify the item. Correct responses were scored 1 point while a less accurate but not incorrect response was scored half point, and the number of correct responses was calculated as the dependent variable.

Visuospatial reasoning (MR). We used the MR subscale of the Wechsler Adult Intelligence Scale (WAIS; Wechsler, 2010) to measure nonverbal visuospatial intelligence. MR is indexing “fluid” intelligence that requires the use of current information in novel problem solving and reasoning. Administration and scoring was performed according to the manual guidelines. Each participant viewed an incomplete matrix of geometric figures and was asked to select the response option that completes the matrix from 6 choice options. Each correct response was scored 1 point, and the number of correct responses was calculated as the dependent variable. Time limit for completing the test was 5 min.

Mental rotation (MRT). The MRT (Phillips, 1979) consists of 20 pairs of depictions of three-dimensional (3D) cube figures designed by Shepard and Metzler (1971). In each pair, the two images are either identical (rotated by a number of degrees) or dissimilar (mirror images) (Figure E, Appendix). Each pair was presented one at time and participants were asked to decide whether the images were the same or different. Each correct response was scored 1 point, and the number of correct responses was calculated as the dependent variable.

Object-based perspective taking (OPT). We used the revised version of the OPT (Hegarty & Waller, 2004; Kozhevnikov & Hegarty, 2001), which assesses the ability to imagine different perspectives or orientations in space. Participants were shown a total of 12 pictures, one at a time. In each picture there is an array of objects as well as an “arrow circle” with a question about the direction between objects from different perspectives (Figure F, Appendix). Participants were instructed to imagine they were standing at one object in the array and facing another object. Then, they were asked to draw an arrow from the centre of the circle pointing to a third object from that facing orientation. Participants were instructed not to mark on the array of objects or rotate the stimulus booklet. Each correct response was scored 1 point, and the number of correct responses was calculated as the dependent variable. The time limit for completing the test was 5 min.

5.2.3.6 Short-term and working memory

Short-term and working memory was examined for verbal (Digit Span task; DS; WMS, Wechsler, 2010), visuospatial (Spatial Span test; SS, Wechsler, 2010), and visual (Matrix Patterns Test; MPT; Riby & Orme, 2013) information.

Verbal (DS). Participants completed the forward condition of the DS (DS-F) as a measure of short-term verbal memory, and the backward condition of the DS (DS-B) as a measure of verbal updating/working memory (Wechsler, 2010). In the forward condition, participants had to repeat a random series of orally presented digits in the same order (e.g., “9-1-7” for 9-1-7). The backward condition was similar to the forward condition, except that the participant had to repeat each series in the reverse order (e.g., “7-1-9” for 9-1-7). In both conditions, the number of digits in each string progressively increased from 2 to 8, and there were two trials for each string length. The presentation rate was one digit per second. The task discontinued when the participant missed both trials of a particular string length in each condition. Memory span was defined as the maximum length of correctly recalled sequences in each condition

Visuospatial (SS). Participants completed the forward condition of the SS (SS-F) as a measure of short-term visuospatial memory, and the backward condition (SS-B) for visuospatial updating/working memory (Corsi, 1972; Wechsler, 2010). In this task, the experimenter pointed to a series of blocks on a board, and the participant had to repeat the sequence of blocks in the same (SS-F) or in the reverse (SS-B) order. In both conditions, the number of blocks progressively increased from 2 to 8, and there were two trials for each length. The presentation rate was one block per second. The task discontinued when the participant missed both trials of a particular length in each condition. Memory span was defined as the longest length of correctly recalled sequences in each condition.

Visual (MS). Several tests using visual matrix patterns have been developed to measure visual memory shorn of its spatio-sequential component (e.g., Della Sala, Gray, Baddeley, Allamano, & Wilson, 1999; Phillips, 1983). In the current study, we used a set of matrix patterns arranged in a way that is difficult to code verbally (thus having a low semantic component) and therefore relying heavily on visual representations (Riby & Orme, 2013). The task comprised of a set of black and white matrices with filled and unfilled cells (Figure G, Appendix). The number of cells progressively increased from 4 to 16, and there were two trials for each difficulty level. Participants were shown each matrix pattern for 4 seconds, and then were asked to reproduce it from memory by marking off squares in an empty matrix of the same size. The task was discontinued when the participant missed both trials of a particular difficulty level. Memory span was defined as the maximum length at which participants reproduced correctly the pattern.

5.2.3.7 Executive functions and processing speed

Processing speed and inhibition (ST). The Stroop task (ST; Stroop, 1935) was used to assess inhibitory control (colours-words condition; ST-CW) as well as speed of processing verbal (word-reading condition; ST-W) and visual information (colour-naming condition; ST-C), according to the administration procedures described by Golden (1976). Each condition occurred at 45 sec intervals. The stimuli consisted of three A4 pages corresponding to one of the three conditions, each with 100 items arranged in five columns of 20 items. In the ST-W condition, the items were colour names (i.e., RED, GREEN, BLUE) randomly arranged in the columns and printed in black ink. Participants were asked to read aloud as many of the words as they can in 45 sec, and therefore, the ST-W condition was used to assess speed of processing verbal material. In the ST-C condition, the items were crosses printed in red, green, or blue ink (e.g., XXX) and participants were asked to name as many colours as they can in 45 sec. Therefore, the ST-C condition was used to evaluate speed of processing visual information. In the incongruent ST-CW condition, the stimuli consisted of the same words of the first condition printed in the colours of the second condition while no word was printed in the colour it represented (e.g., RED). Participants were asked to identify the colour of the ink instead of reading the written words, and therefore, they had to suppress an overlearned response in favour of an unusual one in order to successfully execute the task requirements. An interference score was calculated by regressing the ST-CW score on the ST-C score and saving the unstandardized residual (MacLeod, 1991). Higher scores indicated better performance.

Mental flexibility (TMT-B). The Trail Making test (TMT; Reitan, 1958) was used to assess mental flexibility (or set shifting), as it requires alternating between two serial cognitive sets. The administration procedure was followed as described by Strauss et al. (2006). Participants had to connect with a drawing line a series of numbers and letters in an ascending numerical and alphabetical order while alternating between numbers and letters (i.e., from 1 to A, from A to 2, from 2 to B, and so on), as quickly as possible. In case of error, the participant was notified and encouraged to retrace their steps just before the error.

Participants completed a practice section before completing the test section, in order to ensure their understanding. Performance was based on the time (in seconds) required to successfully complete the task, and so higher scores indicated worse performance. The time required to complete part A was subtracted from the time required to complete part B as an index of mental flexibility.

5.2.3.8 Vocabulary knowledge

We used the multiple-choice version of the Mill Hill Vocabulary Test (MHVT; Raven, 1981) to assess vocabulary knowledge. This test involves selecting a synonym for each test word out of six options. Therefore, it measures the ability to store, process and utilise verbal (semantic) information and knowledge and provides an index of "crystallized" intelligence for semantic information. There is no time limit to complete the task, and performance was based on the total number of correct responses.

5.2.3.9 General cognitive functioning

We used the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005) as a brief measure of general cognitive function, sensitive to detect cognitive impairment. The items of the MoCA evaluate aspects of attention, orientation, language, verbal memory, visuospatial, and executive function, resulting in a 30-point scale. The suggested normal range for the MoCA is between 26 – 30 points, using a one-point education correction (≤ 12 years of formal education) (Damian et al., 2012; Nasreddine et al., 2005). Administration and scoring were according to developers' guidelines, and the cut-off score was set at 25 points.

5.2.3.10 Mood and anxiety

Participants completed the PHQ-9 (Patient Health Questionnaire 9; Kroenke et al., 2001) as a brief measure of depression severity. The PHQ-9 self-report scale consists of 9 items reflecting 9 symptom criteria of depression, and its score can range from 0 to 27, with higher scores suggesting more severe depression. Participants also completed a 21-point self-report scale consisting of 7 items reflecting symptoms of anxiety, the GAD-7 (Generalized Anxiety Disorder 7; Spintzer et al., 2006).

5.2.4 Analysis procedures

There were no missing points in the data set. Data points exceeding 4.0 standard deviations (SD) from the group mean for each variable were considered extreme scores and were replaced by the equivalent mean ± 3.0 SD score (McCartney, Burchinal, & Bub, 2006). This resulted in the adjustment of only three data points. We examined Cook's D in order to assess multivariate outliers, however, there were no measurements greater than 1.0 (Cook, 1977).

After having established the test-retest reliability of the novel spatial language tests (see Section 3.4), we further inspected the distribution of performance on each novel task and examined each task's concurrent and construct validity using a series of hypothesis-driven correlational analyses and an exploratory factor analysis among all measures used. Next, we performed a series of multiple linear regression analyses, in order to examine the influence of demographic factors that may affect performance on each novel task, and subsequently generated appropriately adjusted normative data for the English population. Potential interaction effects of individual differences in age, education, and sex on spatial-verbal performance were examined with multivariate analysis of variance.

Further analyses were performed in order to address the following research questions regarding lifespan performance on spatial-verbal abilities:

1. What are the adult-lifespan trajectories of different aspects of cognition? Are there any age-dependent changes, and if so, when is the onset and nature of changes? Are the changes linear or do they occur at an accelerating rate in the later years of life?
2. Are the age-dependent changes similar across different aspects of spatial language processing and across different cognitive domains or different? Is there a greater change/decline in some domains compared to others?
3. Is the relationship between performance on spatial language tasks and performance on various cognitive tasks stable or it changes across the adult-lifespan?

We employed different statistical methods in order to answer these questions. A series of analyses of (co)variance were conducted in order to examine potential age-related changes, as well as the onset and nature of potential age-related changes in all cognitive measures. Whenever the design included within-subjects variables with more than one conditions (i.e., verbal fluency, naming, episodic memory, verbal comprehension in spatial reference frames), mixed factorial analyses of (co)variance were performed in order to determine the effects of Age Group (between-subjects variable) and Trial Condition (within-subjects variable), and their possible interaction effects on each measure, after controlling for the influence of Education (covariate). Moreover, trend analyses were conducted in order to examine whether a significant polynomial (curvilinear) effect of age on the criterion variables was evident (Tabacknick & Fidell, 2001). When necessary, significant main effects were followed-up with post-hoc group comparisons with Bonferroni correction. Significant main interaction effects were followed up with tests of simple effects with Bonferroni correction, in order to allow comparisons between age groups at any given trial condition across the measures (Tabacknick & Fidell, 2001). Whenever the design did not include within-subjects factors, multivariate analyses of covariance were conducted in order to examine the effects of Age Group on cognitive performance, while controlling for years of formal education (covariate).

The question of whether the age-dependent changes are similar or different across the different aspects of spatial language processing and across different cognitive domains was further approached with a series of regression analyses. A series of correlational analyses and comparisons coefficients (Weaver & Wuensch, 2013) were conducted in order to examine whether the relationships between different measures change across the adult lifespan.

5.3 Results

5.3.1 Distributions of performance on the spatial language tasks

The normality assumption of our data was investigated using the Kolmogorov–Smirnov test for normality, which suggested that all of our variables were normally distributed, except accuracy scores on the relative and intrinsic conditions of the VCSRF task. Descriptive statistics for all novel spatial language variables, including mean, minimum, maximum scores, and their distributions, are presented in Table 9. Results showed that the skewness and kurtosis values for each measure ranged well within acceptable limits of ±2.0 for normally distributed data obtained from large samples (i.e., $N > 150$; Field, 2009; Gravetter & Wallnau, 2014). However, the values for skewness and kurtosis for the relative and intrinsic conditions of the VCSRF task indicated a non-normally distribution of data, reflecting that healthy adults performed close to or at ceiling levels on these conditions. To examine whether this affected the results, all subsequent analyses were conducted twice, once using raw data for these variables and once using log transformations of these variables. Since the results of these analyses did not differ, the analyses based on raw data are presented here. No floor effects were present for any of the performance scores in the novel spatial language measures.

Table 9. *Descriptive Statistics for all Spatial Language Measures*

	Mean	*SD*	*Min*	*Max*	Distribution *Skewness*	Distribution *Kurtosis*
Spatial Verbal Fluency (words)	18.50	6.12	7.00	38.00	.489	.021
Spatial Naming (max=30)	26.20	2.25	11.00	30.00	-.645	.090
Static spatial relations (max=15)	13.00	1.19	6.00	15.00	-.809	.520
Dynamic spatial relations (max=15)	13.20	1.39	6.50	15.00	-.797	.518
Spatial Verbal Memory						
Route						
Immediate recall (max=25)	11.93	3.72	3.00	20.00	.312	-.428
Delayed recall (max=25)	10.84	3.91	3.00	23.00	.327	-.185
Survey						
Immediate recall (max=25)	10.19	3.95	3.00	20.00	.417	-.431
Delayed recall (max=25)	9.67	3.80	2.00	21.00	.565	.001
VCSRF (max=64)	60.11	4.19	43.00	64.00	-1.306	1.481
Self-centred (max=16)	15.99	.08	15.00	16.00	-12.649	160.000
Third-person-centred (max=16)	15.57	1.07	8.00	16.00	-3.970	20.321
Object-centred; max=16)	15.37	1.53	6.00	16.00	-3.794	16.949
Environment-centred; max=16)	13.16	3.21	2.00	16.00	-1.317	1.457

Note. VCSRF = Verbal Comprehension in Spatial Reference Frames; $N = 160$.

5.3.2 Validity assessment of the spatial language tasks

In order to evaluate the concurrent validity of the novel spatial language tests, a series of hypothesis-driven correlational analyses were conducted between each novel spatial language measure, its' analogous non-spatial language measure when appropriate, and several non-verbal visuospatial tasks. Construct validity was further investigated by submitting all measures used to assess spatial language, (non-spatial) language, and (non-verbal) visuospatial abilities to an exploratory factor analysis.

5.3.2.1 Concurrent validity

Results of the correlational analyses with Pearson coefficients for each spatial language measure are presented in Tables 10-13. Analyses revealed high correlations between performance on each spatial language measure and performance on their analogous verbal measures, but also with performance on non-verbal visuospatial measures.

Spatial Verbal Fluency. As it can be seen in Table 10, there were strong correlations between performance on the Spatial Verbal Fluency task and performance on the semantic and phonemic trials of the Verbal Fluency task ($r = .43 – .57$, $p < .001$). Moreover, Spatial

Verbal Fluency was moderately but significantly correlated to performance on putative executive functioning measures (r = .23 – .27, p < .001), including tasks of flexibility (Part B, TMT), inhibition (colours-names, Stroop task), and working memory (backward trials of DS and SS).

Table 10. *Bivariate Correlation Coefficients between Spatial Verbal Fluency and Executive Measures*

	Measure	1	2	3	4	5	6	7	8
1.	Spatial fluency	-	**.46****	**.57****	**.42****	**-.26****	**.26****	**.23****	**.25****
2.	Semantic fluency		-	**.52****	**.44****	**-.30****	**.38****	**.24****	**.20***
3.	Action fluency			-	**.46****	**-.40****	**.42****	**.27****	**.21***
4.	Phonemic fluency				-	**-.36****	**.30****	**.32****	**.20***
5.	Flexibility (Trail B)					-	**-.34****	**-.40****	**.49****
6.	Inhibition (Stroop CN)						-	**.47****	**.50****
7.	Verbal working memory							-	**.32****
8.	Spatial working memory								-

Note. A combined score from the *F*, *A*, and *S* trials was calculated for the Phonemic Verbal Fluency. Significant correlations are in bold. *p < .050, **p < .010 (N = 160).

Spatial Naming Test. As it can be seen in Table 11, naming accuracy for spatial relations was highly correlated with naming accuracy for objects and actions (r = .34 – .41, p < .010), and even higher with performance on visuospatial measures (MR and HVOT) (r = .53 – .54, p < .001). Moreover, the correlation between naming dynamic spatial relations and visuospatial abilities was stronger than the correlation between naming static spatial relations and visuospatial abilities. Meanwhile, performance on object and action naming accuracy was moderately correlated to vocabulary knowledge (MHVT) (r = .22 – .28, p < .050) but not with performance on visuospatial measures (MR and HVOT) (r = .14 – .17).

Table 11. *Bivariate Correlation Coefficients between Naming Accuracy, Vocabulary Knowledge, and Visuospatial Abilities*

	Measure	1	2	3	4	5	6	7	8
1.	Spatial naming	-	**.83****	**.89****	**.41****	**.34****	.10	**.54****	**.53****
2.	Static spatial naming		-	**68****	**.40****	**.33****	.17	**.40****	**.45****
3.	Dynamic spatial naming			-	**.23****	**.27****	.01	**.53****	**.48****
4.	Object naming				-	**.38****	**.28****	.14	.16
5.	Action naming					-	**.22***	.15	.17
6.	Vocabulary knowledge						-	.07	.03
7.	Visuospatial reasoning							-	**.51****
8.	Visual organization								-

Note. Only accuracy of performance is reported for the naming tests. Significant correlations are in bold; * $p < .050$, ** $p < .010$ ($N = 160$).

VCSRF. Accuracy of performance in the self-centred relative condition of the VCSRF task was not related to any other measure ($r = .02 – .12$), possibly because most participants performed at ceiling level. However, accuracies in the third-person-centred relative condition and in the object-centred intrinsic condition were positively correlated with performance on each visuospatial measure (OPT, MRT, HVOT, and MR) ($r = .20 – .37$, $p < .010$). Moreover, accuracy in the environment-centred absolute condition was strongly correlated with (non-verbal) object-based perspective taking (OPT) ($r = .59$, $p < .001$), and moderately to highly related to the rest of the visuospatial measures (MRT, HVOT, and MR) ($r = .34 – .50$, $p < .010$) (Table 12).

Table 12. *Bivariate Correlation Coefficients between Accuracy on the VCSRF task and Measures of Visuospatial Abilities*

	Measure	1	2	3	4	5	6	7	8
1.	VCSRF – Self-C	-	.12	.04	.03	.12	.05	.02	.10
2.	VCSRF – Third-person-C		-	**31****	**.26****	**.37****	**.26****	**.23****	**.27****
3.	VCSRF – Object-C			-	**.25****	**.28****	**.20****	**.20****	**.25****
4.	VCSRF – Environment-C				-	**.59****	**.34****	**.38****	**.50****
5.	Object-perspective taking					-	**.50****	**.42****	**.50****
6.	Mental rotation						-	**.41****	**.47****
7.	Visual organization							-	**.50****
8.	Visuospatial reasoning								-

Note. VCSRF = Verbal Comprehension in Spatial Reference Frames; C = centred. Significant correlations are in bold; * $p < .050$, ** $p < .010$ ($N = 160$).

Spatial Verbal Memory. Delayed recall of both route and survey conditions of the Spatial Verbal Memory task were highly correlated with episodic verbal memory (LM) ($r = .40 – .46$, $p < .010$) as well as with episodic visuospatial memory (ROCF) ($r = .38 – .40$, $p < .010$), visuospatial short-term (MPT and SS-F) and working memory (SS-B) ($r = .27 – .38$, $p < .010$), and with performance on measures of visuospatial abilities (OPT, MRT, HVOT, and MR) ($r = .28 – .44$, $p < .010$) (Table 13). By contrast, episodic verbal memory (LM) was not related to visuospatial memory measures (ROCF, SS-F, SS-B) or to performance on other measures of visuospatial abilities (OPT, MRT, HVOT, and MR) ($r = .10 – .18$).

Table 13. *Bivariate Correlation Coefficients between Spatial-Verbal, Verbal, and Visuospatial Memory Measures, and Visuospatial Measures*

	Measure	1	2	3	4	5	6	7	8	9	10	11	12	13
1.	Episodic SV memory - Route	**-**	**.59****	**.46****	**.40****	**38****	**.29****	**.27****	.16	**.30****	**.28****	**.44****	**.32****	**.40****
2.	Episodic SV memory - Survey		**-**	**.40****	**.38****	**36****	**.30****	**.33****	**.20***	**.26****	**.30****	**.30****	**.36****	**.39****
3.	Episodic verbal memory			**-**	.18	.12	.12	.12	**.26****	**.25****	.10	.15	.18	.18
4.	Episodic visuospatial memory				**-**	**.43****	**.35****	**.37****	.14	**.21****	**.57****	**.42****	**.46****	**.57****
5.	Visual short-term memory					**-**	**.53****	**.52****	**.20***	**.34****	**.47****	**.39****	**.39****	**.54****
6.	Spatial short-term memory						**-**	**.62****	**.20***	**.32****	**.45****	**.37****	**.39****	**.48****
7.	Spatial working memory							**-**	**.20***	**.36****	**.48****	**.38****	**.32****	**.43****
8.	Verbal short-term memory								**-**	**.58****	.19	.18	.10	.17
9.	Verbal working memory									-	**.26****	**.29****	**.23****	**.30****
10.	Object-perspective taking										**-**	**.46****	**.38****	**.51****
11.	Mental rotation											**-**	**.36****	**.51****
12.	Visual organization												-	**.49****
13.	Visuospatial reasoning													-

Note. SV = spatial verbal. Only the delayed recall trials of the episodic memory measures are reported. Significant correlations are in bold; * p < .050, ** p < .010 (N = 160).

5.3.2.2 Construct validity

All tests were submitted to an exploratory factor analysis with principal axis factoring as the extraction method with initial eigenvalues greater than 1.0 followed by varimax rotation and Kaiser normalization, which suggested a six-factor solution. At baseline, the eigenvalue of Factor 1 was 8.46 before rotation and accounted for 35.27% of the variance, while the eigenvalues of Factors 2 to 6 ranged between 1.73 and 1.0 and they accounted for 28.83% of the variance. After rotation, the six-factor solution accounted for 52.21% of the total variance explained.

Rotated factor loadings for the six-factor solution are presented in Table 14. All measures tapping visuospatial abilities (OPT, MRT, HVOT, and MR), along with tasks of visuospatial memory (ROCF, MPT, SS-F, SS-B), loaded on Factor 1, which accounted for 17.27% of the variance explained. Spatial Verbal Fluency loaded along with animal, action, and phonemic fluency on Factor 2, which accounted for 10.10% of the variance. Episodic spatial-verbal memory for route and survey descriptions loaded along with episodic verbal memory (LM) on Factor 3, accounting for 8.03% of the variance. Notably, route and survey spatial-verbal memory were also related to Factor 1, while episodic verbal memory (LM) was not. Spatial naming (SNT) loaded along with object (BNT) and action (ANT) naming on Factor 4, explaining 7.46% of the variance. Importantly, spatial naming also had a strong loading on Factor 1, while object and action naming did not. Accuracy in the absolute condition of the VCSRF loaded on Factor 1, along with visuospatial measures. Verbal short-term (SS-F) and working (SS-B) memory measures loaded on Factor 5, accounting for 6.93% of the variance, while vocabulary knowledge (MHVT) was the sole measure loading on factor 6, which accounted for just 2.5% of the variance explained. Finally, Part B of the TMT loaded solely on Factor 1, possibly because it also relies on visual search and scanning recourses apart from mental flexibility (set-shifting) skills, while inhibitory control as assessed with Stroop task (colours-words), had a moderate loading on Factor 1 and weak loadings on Factors 2 and 5.

Table 14. *Factor Loadings from the Exploratory Factor Analysis after Oblimin Rotation*

	Factor					
Construct (and measures)	1	2	3	4	5	6
Fluency						
Spatial fluency	.25	**.62**	.26	.11	.00	.21
Semantic fluency	.22	**.60**	.25	.15	.03	.16
Action fluency	.26	**.63**	.13	.29	.05	.13
Phonemic fluency	.15	**.65**	-.01	.08	.28	.10
Naming						
Spatial naming	**.51**	.28	.14	**.51**	.24	.14
Object naming	.07	.29	.18	**.51**	.04	.15
Action naming	.22	.07	.11	**.57**	.01	.07
Episodic memory						
Spatial verbal memory - Route	.31	.15	**.75**	.16	.08	.15
Spatial verbal memory - Survey	.34	.15	**.69**	.14	.04	.03
(Non-spatial) Verbal memory	.03	.10	**.58**	.10	.18	.10
(Non-verbal) Visuospatial memory	**.55**	.24	.19	.32	-.02	.13
Spatial perspective taking						
Absolute condition - VCSRF	**.56**	.11	.10	.39	.05	-.01
Object-perspective taking	**.69**	.11	.10	.26	.02	.17
Visuospatial processing						
Mental rotation	**.51**	.18	.27	.03	.13	.19
Visuospatial reasoning	**.59**	.27	.22	.24	.11	.07
Visual organization	**.50**	.19	.20	.37	.01	-.02
Short-term and working memory						
Verbal short-term memory	.18	.06	.12	-.01	**.74**	.09
Verbal working memory	.25	.15	.20	.09	**.74**	.12
Visual short-term memory	**.54**	.10	.22	.29	.13	-.12
Spatial short-term memory	**.57**	.15	.08	.09	.21	.01
Spatial working memory	**.66**	.07	.03	-.02	.18	.04
Flexibility (& visual search)	**-.60**	-.29	-.13	-.16	-.28	.10
Inhibition	.49	.39	.01	.29	.36	-.28
Vocabulary	.09	.21	-.03	.16	.23	**.49**

Note. VCSRF = Verbal Comprehension in Spatial Reference Frames. Strong loadings are in bold.

5.3.3 Influence of demographic factors and normative data

In order to examine the potential contribution of demographic factors (i.e., age, education, and gender) to performance on each spatial language measure, we applied a series of multiple linear regression analyses. The results of these analyses are presented in Table 15. Moreover, we performed a series of ANOVAs in order to examine potential interaction effects of the demographic variables on spatial-verbal abilities, as assessed with the novel spatial language tasks. To that end, and in order to obtain normative data for the English adult population, we grouped our sample into demographic categories. We stratified our sample into five age groups (in decades): 18–28, 45–54, 55–64, 65–74, and 75–85. Education was converted into a discrete variable with two levels: 0-13 years, reflecting the compulsory education period in the UK, and 14 years or above for higher education level (at least one year in higher education institutions).

Table 15. *Contribution of Age, Gender, and Education to Performance on Spatial Language Measures*

Variable	Factor	*B*	*SE B*	*β*	*t*	*p*
Spatial verbal fluency						
	Age	-0.04	0.18	-0.16	-2.05	**.042**
	Education	0.37	0.11	0.24	3.21	**.002**
	Gender	-1.23	0.73	-0.12	-1.68	.093
Spatial naming						
Static spatial naming						
Accuracy	Age	-0.01	0.00	-0.16	-2.11	**.036**
	Education	0.10	0.02	0.27	3.60	< **.001**
	Gender	-0.32	0.18	-0.13	-1.80	.077
Speed	Age	0.88	0.09	0.58	8.89	< **.001**
	Education	-0.69	0.65	-0.07	-1.06	> .250
	Gender	5.04	4.16	0.08	1.21	> .250
Dynamic spatial naming						
Accuracy	Age	-0.03	0.00	-0.41	-6.12	< **.001**
	Education	0.12	0.02	0.26	3.99	< **.001**
	Gender	-0.67	0.18	-0.23	-3.60	< **.001**
Speed	Age	0.52	0.06	0.53	8.14	< **.001**
	Education	-1.03	0.41	-0.16	-2.45	**.015**
	Gender	4.94	2.66	0.12	1.86	.065
Spatial verbal memory						
Route						
Immediate recall	Age	-0.09	0.01	-0.26	-3.50	**.001**
	Education	0.21	0.90	0.18	2.40	**.016**
	Gender	-0.87	0.56	-0.11	-1.56	.122
Delayed recall	Age	-0.05	0.01	-0.26	-3.59	< **.001**
	Education	0.25	0.09	0.20	2.75	**.007**
	Gender	-1.34	0.58	-0.16	-2.29	**.023**
Survey						
Immediate recall	Age	-0.06	0.01	-0.30	-3.97	< **.001**
	Education	0.08	0.09	0.06	.88	> .250

	Gender	-0.76	0.61	-0.08	-1.11	> .250
Delayed recall	Age	-0.06	0.01	-0.31	-4.15	**< .001**
	Education	0.15	0.09	0.12	1.63	.104
	Gender	-0.63	0.58	-0.08	-1.09	> .250
Verbal comprehension in spatial reference frames						
Self-centred						
Accuracy	Age	0.00	0.00	-0.06	-0.85	> .250
	Education	0.00	0.00	0.06	0.81	> .250
	Gender	-0.01	0.01	-0.06	-0.82	> .250
Speed	Age	0.19	0.02	0.52	8.26	**< .001**
	Education	-0.56	0.15	-0.24	-3.87	**< .001**
	Gender	-0.20	0.98	-0.01	-0.20	> .250
Third-person-centred						
Accuracy	Age	-0.08	0.04	-0.14	-2.05	**.049**
	Education	0.04	0.08	0.28	1.61	.109
	Gender	-0.19	0.17	-0.09	-1.15	> .250
Speed	Age	0.30	0.03	0.55	8.66	**< .001**
	Education	-0.76	0.22	-0.21	-3.36	**.001**
	Gender	0.07	1.43	0.00	0.05	> .250
Object-centred						
Accuracy	Age	0.00	0.01	0.01	0.08	> .250
	Education	0.08	0.04	0.10	1.78	.069
	Gender	-0.31	0.24	-0.10	-1.26	> .250
Speed	Age	0.23	0.03	0.49	7.37	**< .001**
	Education	-0.75	0.20	-0.24	-3.68	**< .001**
	Gender	0.49	0.30	0.02	0.39	> .250
Environment-centred						
Accuracy	Age	-0.03	0.01	-0.20	-2.69	**.008**
	Education	0.25	0.07	0.25	3.34	**.001**
	Gender	-1.41	0.48	-0.22	-2.95	**.004**
Speed	Age	0.40	0.05	0.51	7.92	**< .001**
	Education	-1.30	0.33	-0.25	-3.93	**< .001**
	Gender	2.45	2.08	0.07	1.18	.240

Note. N = 160.

5.3.3.1 Spatial verbal fluency

Results yielded that age and education contributed significantly to performance on Spatial Verbal Fluency (SVF), $F(3, 156) = 5.86$, $p = .001$, $R^2 = .10$ (Table 15; for detailed results regarding the age effects on verbal fluency, see Section 5.3.4.1). Individuals with higher education generated more spatial language terms during the testing period (0-13 years of formal education: $M = 11.73$, $SD = 3.28$; 14+ years of formal education: $M = 14.12$, $SD = 4.82$). Overall, men generated more words compared to women (males: $M = 13.90$, $SD = 4.71$; females: $M = 12.68$, $SD = 4.73$), but gender did not reach significance as a predictive factor. There were no interaction effects among the three demographic factors on the number of words produced in the SVF task. The normative data for means, standard deviations and percentile performance stratified by age and education are presented in Table 16.

Table 16. *Normative Data for Spatial Verbal Fluency (Number of Words Produced) Stratified by Age and Education*

	Age									
	18-28 years (*n* = 34)		45 – 54 years (*n* = 30)		55 – 64 years (*n* = 32)		65 – 74 years (*n* = 32)		75 – 85 years (*n* = 32)	
	Education (years)		Education (years)		Education (years)		Education (years)		Education (years)	
Percentile	1-13	13+	1-13	13+	1-13	13+	1-13	13+	1-13	13+
90	13.0	19.6	17.0	25.2	19.4	22.0	20.2	21.4	17.4	18.0
80	13.0	17.0	16.2	23.2	17.4	20.6	15.8	15.6	14.0	14.6
70	12.0	15.2	13.0	19.0	15.2	18.0	14.2	14.5	13.0	14.0
60	12.0	14.0	12.8	17.2	11.8	15.0	10.8	13.0	12.0	12.8
50	11.0	13.0	12.0	16.0	10.5	13.5	10.0	12.5	11.5	12.0
40	10.0	13.2	10.4	15.0	10.0	12.5	9.2	12.0	10.0	11.6
30	10.0	12.0	8.8	13.0	8.9	12.0	9.0	10.0	8.5	10.0
20	9.0	11.2	7.6	12.8	7.6	10.0	7.6	8.4	7.0	9.8
10	8.0	9.6	7.0	9.6	5.2	8.1	4.8	6.6	6.0	7.4
M	11.44	14.1	12.0	16.7	11.6	14.4	11.3	12.6	11.2	12.1
SD	2.92	3.7	4.6	5.4	4.9	4.8	4.8	4.5	4.2	4.1

5.3.3.2 Spatial naming

Results showed that all demographic variables contributed significantly to spatial naming accuracy, $F(3, 156) = 21.11$, $p < .001$, $R^2 = .29$ (Table 15; for detailed results regarding age effects on naming abilities, see Section 5.3.4.4). Individuals with higher education were more accurate in naming spatial relations between objects (0-13 years: *M* = 25.33, *SD* = 2.46; 14+ years: *M* = 26.21, *SD* = 1.91). Men, independent of age and educational level, were more accurate in spatial naming compared to women (males: *M* = 26.8, *SD* = 2.04; females: *M* = 25.79, *SD* = 2.3). There were no interaction effects among the three demographic factors on spatial naming accuracy. The normative data for means, standard deviations and percentile performance on the SNT stratified by age, education, and gender are presented in Table 17.

We further analysed the influence of demographic variables on naming accuracy for static and dynamic spatial relations, separately. Results yielded age and education as significant predictors of naming static spatial relations, $F(3, 156) = 7.76$, $p < .001$, $R^2 = .13$, while age, education, and gender contributed significantly to naming accuracy for dynamic spatial relations, $F(3, 156) = 25.15$, $p < .001$, $R^2 = .32$ (Table 15), while there were no interaction effects. Accuracy for both naming conditions was increased in participants who were younger and those who had more years of formal education (Static: 0-13: $M = 12.58$, $SD = 1.31$; 14+: $M = 13.27$, $SD = 1.02$; Dynamic: 0-13: $M = 12.73$, $SD = 1.53$; 14+: $M = 13.5$, $SD = 1.21$). Males were significantly more accurate in naming dynamic spatial relations compared to women (males: $M = 13.6$, $SD = 1.12$; females: $M = 12.92$, $SD = 1.5$), but the sex differences did not reach significance for the naming accuracy in static spatial relations (males: $M = 13.19$, $SD = 1.12$; females: $M = 12.87$, $SD = 1.19$). The normative data for accuracy of naming static and dynamic spatial relations are presented in Tables 18 and 19, respectively.

Regarding spatial naming speed, results yielded that age was the only significant variable affecting time required to complete both parts of the SNT, $F(3, 156) = 25.64$, $p < .001$, $R^2 = .33$. Age was the only significant predictor of speed of performance in static spatial naming, $F(3, 156) = 27.36$, $p < .001$, $R^2 = .34$, with younger participants being faster than older participants. Apart from age, education also contributed significantly to speed of naming dynamic spatial relations, $F(3, 156) = 27.98$, $p < .001$, $R^2 = .35$, with younger and more educated individuals being faster.

Table 17. *Normative Data for Accuracy of Naming Static Spatial Relations (SNT-S)*

	Age									
	18-28 years (*n* = 34)		45 – 54 years (*n* = 30)		55 – 64 years (*n* = 32)		65 – 74 years (*n* = 32)		75 – 85 years (*n* = 32)	
	Education (years)		Education (years)		Education (years)		Education (years)		Education (years)	
Percentile	1-13	13+	1-13	13+	1-13	13+	1-13	13+	1-13	13+
90	14.1	14.5	15.0	15.0	14.5	15.0	14.5	15.0	14.0	14.0
80	14.0	13.6	14.5	14.8	14.0	14.5	14.3	14.5	13.5	13.4
70	13.9	13.1	14.5	14.2	14.0	14.0	13.5	13.5	13.0	13.0
60	13.5	13.0	14.5	14.0	13.7	14.0	13.5	13.0	12.9	12.5
50	13.5	12.5	14.0	14.0	13.5	13.0	13.5	13.0	12.5	12.0
40	13.5	12.5	14.0	13.5	13.1	13.0	13.2	12.5	12.1	11.7
30	13.0	12.0	14.0	13.3	12.2	12.5	12.9	12.0	11.5	11.1
20	12.7	11.9	14.0	12.5	11.3	12.0	12.1	11.5	11.0	11.0
10	12.3	11.0	13.0	12.0	10.5	11.5	11.5	10.5	10.6	9.6
M	13.4	12.7	14.1	13.4	13.0	13.5	13.2	12.5	12.3	12.0
SD	0.6	1.0	0.5	1.0	1.4	0.7	1.0	1.1	1.1	1.4

Table 17. *Normative data for Accuracy of Performance on the Spatial Naming Test Stratified by Age, Education, and Gender*

	Age																			
	18 – 28 years (*n* = 34)				45 – 54 years (*n* = 34)				55 – 64 years (*n* = 34)				65 - 74 years (*n* = 34)				75 – 85 years (*n* = 34)			
	Males		Females		Males		Females		Males		Females		Males		Females		Males		Females	
	Education		Education		Education		Education		Education		Education		Education		Education		Education		Education	
Percentile	0-13	14+	0-13	14+	0-13	14+	0-13	14+	0-13	14+	0-13	14+	0-13	14+	0-13	14+	0-13	14+	0-13	14+
90	28.0	29.2	27.5	29.2	29.7	29.5	28.5	29.6	28.6	28.8	28.0	28.8	29.0	27.9	28.6	26.5	26.4	27.9	25.5	26.5
80	28.0	29.0	27.1	27.6	29.7	29.5	28.0	29.0	28.6	28.8	27.0	28.1	29.0	27.9	28.6	26.5	26.4	27.9	25.1	26.5
70	27.8	28.2	26.5	27.0	29.7	29.3	27.3	28.4	27.7	28.0	26.4	28.0	27.0	27.0	27.4	26.5	25.6	26.1	23.9	26.0
60	27.8	28.0	26.4	27.0	29.0	29.0	26.2	27.5	26.0	28.0	26.1	27.4	26.5	27.0	26.7	26.0	25.0	25.3	23.1	25.5
50	27.5	27.7	26.0	26.5	28.8	29.0	25.0	27.5	24.5	28.0	26.0	27.0	26.5	26.7	26.5	24.5	25.0	25.0	22.5	24.5
40	27.2	27.5	26.0	25.9	28.5	29.0	24.7	27.4	23.5	27.0	25.9	26.5	26.5	26.5	25.1	24.5	25.0	24.4	21.9	23.5
30	27.0	27.5	26.0	25.5	28.5	28.4	24.0	27.0	23.5	26.5	25.5	25.5	25.5	26.5	22.5	24.0	23.5	23.7	21.5	23.0
20	27.0	26.0	25.4	25.2	28.0	27.2	22.5	26.5	22.9	26.3	24.0	25.5	25.0	24.1	21.4	24.0	22.3	22.8	21.5	22.0
10	26.5	25.7	24.5	24.2	28.0	26.0	22.0	25.5	22.5	26.0	23.0	25.0	24.5	22.5	21.0	24.0	22.0	22.5	19.5	20.0
M	27.4	27.6	26.0	26.4	29.0	28.5	25.4	24.5	25.3	27.4	26.0	26.9	26.6	26.3	25.3	25.5	24.6	25.1	22.7	24.4
SD	.7	1.1	1.2	1.5	1.0	1.2	2.4	1.3	2.6	1.3	1.9	1.3	1.1	2.0	3.1	1.4	1.7	2.2	1.9	2.6

Table 18. *Normative Data for Accuracy of Performance on the Dynamic Spatial Naming Test Stratified by Age, Education, and Gender*

	Age																			
	18 – 28 years (*n* = 34)				45 – 54 years (*n* = 34)				55 – 64 years (*n* = 34)				65 - 74 years (*n* = 34)				75 – 85 years (*n* = 34)			
	Males		Females		Males		Females		Males		Females		Males		Females		Males		Females	
	Education		Education		Education		Education		Education		Education		Education		Education		Education		Education	
Percentile	0-13	14+	0-13	14+	0-13	14+	0-13	14+	0-13	14+	0-13	14+	0-13	14+	0-13	14+	0-13	14+	0-13	14+
90	14.5	15.0	14.5	14.5	15.0	15.0	14.5	15.0	14.8	14.4	14.6	15.0	14.5	13.8	14.6	14.5	13.2	14.5	12.4	13.5
80	14.5	15.0	14.4	14.3	15.0	15.0	14.0	15.0	14.8	14.4	14.6	14.2	14.5	13.8	14.6	14.5	13.2	14.2	12.0	13.5
70	14.2	15.0	14.0	14.0	15.0	15.0	13.6	14.5	14.3	14.0	13.9	14.0	14.0	13.5	13.8	13.5	12.8	13.3	12.0	13.0
60	14.2	14.5	14.0	13.6	15.0	15.0	12.9	14.1	13.3	14.0	13.6	14.0	14.0	13.5	13.2	13.0	12.5	12.8	11.6	12.5
50	13.7	14.5	14.0	13.5	14.7	14.0	12.0	14.0	13.0	14.0	13.2	13.0	13.0	13.2	12.7	13.0	12.5	12.5	11.5	12.5
40	13.3	14.0	13.6	13.0	14.5	14.0	12.0	14.0	12.8	13.5	12.7	12.8	13.0	13.0	12.5	12.0	12.1	12.5	10.4	12.0
30	13.0	14.0	13.5	13.0	14.5	14.0	11.9	13.5	12.1	13.4	11.6	12.5	12.5	13.0	12.0	12.0	11.7	12.3	10.0	11.5
20	13.0	13.5	13.3	13.0	14.0	13.6	11.6	13.2	12.0	12.8	10.6	12.0	12.5	12.1	10.7	1.5	11.3	11.7	9.7	10.5
10	13.0	13.0	13.0	12.0	14.0	13.0	11.5	12.5	12.0	12.5	10.0	11.7	11.5	11.5	9.5	11.5	11.0	11.5	9.1	8.5
M	13.7	14.2	13.8	13.5	14.7	14.5	12.6	14.0	13.2	13.7	12.8	13.2	13.4	13.0	12.6	12.9	12.2	12.8	10.9	12.1
SD	1.0	.6	.6	.8	.3	.7	1.1	.8	1.2	.8	1.8	1.1	1.2	.8	1.8	1.2	.8	1.1	1.1	1.8

5.3.3.3 Spatial verbal memory

Route. Age and education contributed significantly to the immediate recall trial of the SVM-R task, $F(3, 156) = 7.98$, $p < .001$, $R^2 = .13$, with better performance among younger participants and those with a higher level of education (Table 15; For detailed results regarding the age effects on memory, see Section 5.3.4.3; 0-13 years: $M = 10.81$, $SD = 3.3$; 14+ years: $M = 12.65$, $SD = 3.81$), while there was a non-significant trend for a male advantage in the immediate recall of the SVM-R. Age, education, and sex contributed significantly to the delayed recall trial of the SVM-R, $F(3, 156) = 9.77$, $p < .001$, $R^2 = .16$. Increased age and lower education were related to poorer performance (Table 15; 0-13 years: $M = 9.6$, $SD = 3.45$; 14+ years: $M = 11.64$, $SD = 3.98$), whereas men retained significantly more spatial information from a route perspective after a 30-min delay compared to women (males: $M = 11.64$, $SD = 3.86$; females: $M = 10.29$, $SD = 3.87$). There were no interaction effects of the demographic variables on the immediate and delayed recall trials of the SVM-R. The normative data for the immediate and delayed recall trials in the SVM-R are presented in Tables 20 and 21, respectively.

Table 20. *Normative Data for Immediate Recall in the Route Spatial-Verbal Memory task Stratified by Age and Education*

	Age									
	18-28 years (*n* = 34)		45 – 54 years (*n* = 30)		55 – 64 years (*n* = 32)		65 – 74 years (*n* = 32)		75 – 85 years (*n* = 32)	
	Education (years)		Education (years)		Education (years)		Education (years)		Education (years)	
Percentile	1-13	14+	1-13	14+	1-13	14+	1-13	14+	1-13	14+
90	19.4	19.0	15.0	19.2	14.7	19.9	15.6	16.0	13.2	17.5
80	15.8	17.0	14.2	17.2	13.4	17.0	14.0	13.5	12.0	16.0
70	14.2	15.0	12.6	16.0	12.1	14.0	12.6	11.0	11.0	13.0
60	13.2	14.0	11.6	16.0	11.8	13.6	11.0	11.0	10.4	12.0
50	12.0	14.0	10.0	15.0	10.5	12.5	10.0	10.0	10.0	12.0
40	11.0	14.0	8.4	14.6	9.2	11.0	9.0	9.0	9.0	11.0
30	10.8	12.0	7.4	13.0	9.0	9.6	9.0	8.8	8.0	9.5
20	10.0	11.0	6.4	12.0	8.6	8.0	8.0	7.2	7.0	7.0
10	9.0	9.0	6.0	10.4	6.0	7.1	6.8	6.5	6.9	5.5
M	12.8	14.1	10.1	14.7	10.5	12.6	10.7	10.2	9.7	11.5
SD	3.6	3.3	4.2	3.1	2.8	4.2	3.2	2.8	2.4	3.9

Table 21. *Normative Data for the Delayed Recall in the Route Spatial Verbal Memory task Stratified by Age, Gender, and Education*

	Age																			
	18 – 28 years (*n* = 34)				45 – 54 years (*n* = 34)				55 – 64 years (*n* = 34)				65 - 74 years (*n* = 34)				75 – 85 years (*n* = 34)			
	Males		Females		Males		Females		Males		Females		Males		Females		Males		Females	
	Education		Education		Education		Education		Education		Education		Education		Education		Education		Education	
Percentile	0-13	14+	0-13	14+	0-13	14+	0-13	14+	0-13	14+	0-13	14+	0-13	14+	0-13	14+	0-13	14+	0-13	14+
90	15.0	21.0	15.0	17.0	16.5	18.5	14.0	17.5	13.0	16.5	13.0	16.6	13.0	12.0	13.0	16.0	11.0	14.0	14.2	16.0
80	15.0	19.0	13.5	16.8	16.5	18.4	11.0	16.0	12.8	16.0	12.2	13.6	13.0	10.8	12.4	16.0	10.0	12.8	10.6	16.0
70	14.0	17.0	11.4	15.6	16.5	17.2	10.0	14.0	10.8	16.0	10.8	12.6	12.0	10.0	11.3	11.0	10.0	12.2	10.0	13.0
60	13.6	15.0	10.2	14.8	16.4	16.0	10.0	14.0	9.4	15.0	9.4	11.0	12.0	9.0	9.8	11.0	9.6	11.2	9.2	12.0
50	13.0	13.5	10.0	14.0	14.0	16.0	9.0	13.5	9.0	11.0	8.5	11.0	10.0	8.5	8.5	9.0	8.0	10.0	9.0	11.0
40	12.4	11.0	10.0	10.0	11.6	14.5	8.0	12.6	8.8	10.2	7.6	10.0	10.0	7.8	8.0	8.0	8.0	9.4	8.6	10.0
30	12.0	11.0	8.0	9.0	10.0	13.4	7.0	11.0	8.1	8.2	6.2	9.0	10.0	7.1	6.8	8.0	7.4	8.8	6.6	7.0
20	11.0	11.0	8.0	8.0	10.0	11.4	6.0	9.0	8.0	7.0	5.5	7.8	9.0	6.0	5.0	7.0	6.6	8.2	5.4	5.0
10	10.0	8.5	7.5	6.0	10.0	9.0	5.0	8.5	8.0	7.0	5.0	6.0	7.0	6.0	4.0	6.0	6.0	8.0	4.2	4.4
M	12.8	14.1	10.1	12.5	14.0	15.0	9.0	12.8	9.8	11.8	8.5	11.1	10.8	9.3	8.7	10.5	8.4	10.4	8.6	10.3
SD	2.1	4.4	2.6	4.4	5.6	3.3	3.3	3.2	2.3	4.1	3.2	3.7	2.3	2.6	3.5	4.3	1.6	2.0	3.1	4.7

Survey. Age alone contributed to the immediate, $F(3, 156) = 5.92$, $p < .001$, $R^2 = .1$, and delayed, $F(3, 156) = 7.07$, $p < .001$, $R^2 = .12$, recalls in the survey condition of the spatial-verbal memory task, with older age associated to lower memory performance (Table 15; For detailed results regarding the age effects on memory, see Section 5.3.4.3). Nevertheless, there was also a significant interaction effect between Age Group and Gender on the immediate recall of the allocentric spatial verbal memory, $F(4, 159) = 3.36$, $p = .012$, *partial* $\eta^2 = .08$. Follow-up simple main effects of gender were significant for individuals aged between 18 and 54 ($p < .001$), with higher scores for men (Table 22). Normative data stratified by age and gender for the immediate and delayed recall in the SVM-S task are presented in Tables 22 and 23, respectively.

Table 22. *Normative Data for the Immediate Recall in the Survey Spatial-Verbal Memory task Stratified by Age and Gender*

	Age									
	18 – 28 years (*n* = 34)		45 – 54 years (*n* = 30)		55 – 64 years (*n* = 32)		65 – 74 years (*n* = 32)		75 – 85 years (*n* = 32)	
Percentile	Males	Females	Males	Females	Males	Females	Males	Females	Males	Females
90	18.6	16.0	20.0	16.0	18.0	16.0	12.4	15.8	11.1	15.0
80	15.2	11.0	19.0	14.2	13.2	11.0	11.8	13.4	9.5	13.6
70	13.5	10.0	18.0	12.4	11.8	10.0	10.2	12.6	9.5	11.0
60	13.0	9.5	16.0	11.0	11.0	9.0	10.0	11.0	9.0	9.6
50	13.0	9.0	14.5	10.0	9.0	9.5	9.0	10.0	9.0	9.0
40	12.8	7.5	14.0	8.8	8.2	7.0	7.4	9.0	8.2	7.4
30	12.0	7.0	14.0	8.0	7.0	7.5	6.0	7.4	6.0	6.0
20	9.4	6.0	12.0	7.5	6.8	6.0	5.0	6.0	5.2	5.2
10	8.0	5.0	8.0	4.5	5.4	5.0	4.0	5.0	4.0	4.1
M	12.8	10.9	14.8	10.2	10.1	9.0	8.3	10.1	7.8	9.1
SD	3.2	4.1	3.5	3.8	4.1	3.2	3.1	3.8	2.3	4.0

Table 23. *Normative Data for the Delayed Recall in the Survey Spatial-Verbal Memory task Stratified by Age and Gender*

	Age									
	18 – 28 years (*n* = 34)		45 – 54 years (*n* = 30)		55 – 64 years (*n* = 32)		65 – 74 years (*n* = 32)		75 – 85 years (*n* = 32)	
Percentile	Males	Females	Males	Females	Males	Females	Males	Females	Males	Females
90	16.2	16.1	21.0	17.0	18.0	14.0	11.0	15.0	11.0	12.0

80	13.6	14.2	20.0	16.2	13.2	11.0	10.0	11.6	9.5	11.8
70	13.0	12.3	17.0	13.4	11.0	10.0	10.0	9.0	9.0	11.0
60	13.0	11.0	14.0	11.0	10.4	9.0	9.6	9.0	9.0	10.6
50	12.5	11.0	12.0	11.0	10.0	8.0	9.0	8.0	9.0	9.0
40	12.0	10.0	12.0	8.8	9.2	7.0	8.0	8.5	8.2	6.8
30	11.1	8.0	11.0	7.6	7.2	6.0	7.6	7.0	6.0	6.0
20	8.4	7.0	10.0	7.0	5.8	5.0	6.0	6.0	5.2	5.2
10	7.0	5.0	6.0	5.0	4.5	5.0	4.0	5.0	4.0	5.0
M	11.9	10.5	13.6	10.5	10.0	8.3	8.2	8.8	7.1	8.7
SD	3.1	4.1	4.8	4.5	4.3	3.4	2.3	3.1	1.1	3.2

5.3.3.4 Comprehension in spatial reference frames

The regression models were non-significant for the accuracy of performance on the self-centred relative, $F(3, 156) = .76$, $p > .250$, $R^2 = .01$, and on the object-centred intrinsic, $F(3, 156) = 1.92$, $p = .127$, $R^2 = .03$, conditions of the VCSRF. Age significantly contributed to performance on the third-centred condition, $F(3, 156) = 4.69$, $p = .048$, $R^2 = .08$, with older age associated with poorer performance (Table 15; For detailed results regarding the age effects on VCSRF performance, see Section 5.3.4.2). Accuracy of performance within the environment-centred condition was predicted by age, education, and sex, $F(3, 156) = 10.09$, $p < .001$, $R^2 = .16$, with younger, more educated, and male individuals achieving higher scores (level of education: 0-13: $M = 12.42$, $SD = 3.61$; 14+: $M = 13.56$, $SD = 1.7$; sex: males: $M = 13.95$, $SD = 1.53$; females: $M = 12.54$, $SD = 3.23$). There were no interaction effects amongst the demographic variables on accuracy of performance in any of the VCSRF conditions. Table 24 shows the norms for accuracy on the absolute condition of the VCSRF.

Speed of performance was predicted by age in the self-centred condition, $F(3, 156) = 31.64$, $p < .001$, $R^2 = .38$, with older age associated to reduced speed. Both age and education contributed significantly to speed of performance on the third-person-centred, $F(3, 156) = 32.39$, $p < .001$, $R^2 = .38$ (0-13: $M = 12.42$, $SD = 3.61$; 14+: $M = 13.56$, $SD = 1.7$), object-centred, $F(3, 156) = 25.97$, $p < .001$, $R^2 = .33$ (0-13: $M = 58.12$, $SD = 10.61$; 14+: $M = 52.35$, $SD = 8.6$), and environment-centred, $F(3, 156) = 30.37$, $p < .001$, $R^2 = .37$ (0-13: $M = 89.9$, $SD = 15.72$; 14+: $M = 81.21$, $SD = 15.7$), conditions, with younger and more educated participants being faster.

Table 24. *Normative Data for Accuracy in the Environment-Centred Condition of the VCSRF*

	Age																			
	18 – 28 years (*n* = 34)				45 – 54 years (*n* = 34)				55 – 64 years (*n* = 34)				65 - 74 years (*n* = 34)				75 – 85 years (*n* = 34)			
	Males		Females		Males		Females		Males		Females		Males		Females		Males		Females	
	Education		Education		Education		Education		Education		Education		Education		Education		Education		Education	
Percentile	0-13	14+	0-13	14+	0-13	14+	0-13	14+	0-13	14+	0-13	14+	0-13	14+	0-13	14+	0-13	14+	0-13	14+
90	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	15.5	16.0	16.0	15.6	15.5	15.0	15.2	15.0	15.0	15.0
80	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	15.2	16.0	16.0	15.6	15.2	15.0	15.0	15.0	13.4	15.0
70	15.5	16.0	15.2	15.5	15.0	16.0	16.0	16.0	16.0	16.0	13.8	16.0	16.0	15.0	15.0	15.0	15.0	15.0	10.4	14.0
60	15.0	16.0	13.8	14.5	14.6	15.8	15.6	15.2	16.0	16.0	12.4	15.4	15.0	15.0	14.4	14.0	13.8	13.8	9.2	11.0
50	14.5	16.0	13.0	14.0	12.5	15.0	15.0	15.0	15.0	16.0	11.0	14.0	15.0	15.0	14.0	14.0	13.0	12.0	9.0	10.0
40	14.0	15.0	11.5	14.0	12.0	15.0	12.6	14.0	13.8	15.5	10.0	13.6	15.0	14.6	13.6	14.0	9.0	11.4	9.0	8.0
30	14.0	15.0	10.5	12.8	10.4	14.0	10.2	12.2	13.1	15.0	10.0	11.4	15.0	13.2	12.1	13.0	5.0	11.0	9.2	7.0
20	14.0	14.0	9.5	11.6	9.0	14.0	8.0	11.4	9.4	13.0	9.4	11.0	14.0	12.4	9.0	13.0	5.0	11.0	8.4	5.0
10	11.0	14.0	9.0	10.4	9.0	13.0	7.0	10.4	7.0	10.0	9.0	9.2	10.0	12.0	5.0	12.0	4.0	11.0	7.2	3.0
M	14.3	15.3	12.7	13.0	13.0	15.0	13.0	14.0	13.6	15.0	11.8	13.6	14.5	14.1	12.7	13.9	10.4	12.8	10.1	10.1
SD	1.6	.8	2.8	2.5	4.5	1.0	3.9	2.2	3.5	2.2	2.7	2.6	2.3	1.5	3.6	1.0	5.7	2.1	2.6	4.1

5.3.4 Adult-lifespan trajectories

5.3.4.1 Visuospatial abilities, vocabulary knowledge, and processing resources

A series of analyses of variance were executed to determine the effects of age and gender on tasks assessing visuospatial abilities, vocabulary knowledge, and core processing resources after controlling for educational level. Significant effects were followed up with Bonferroni-corrected group comparisons. Results of these analyses are presented in Table 25.

Table 25. *Multivariate Analyses of Covariance for the Effect of Age on all Measures*

Measure	*F*	df, error df	*p*	Partial η^2	Post-hoc group comparisons
Visuospatial abilities					
Mental rotation	4.35	4, 154	**.002**	.10	18-28 > 75-85 ($p \leq .038$)
Object-perspective taking	8.38	4, 154	**< .001**	.17	18-28 > 55-85 ($p \leq .011$) 45-74 > 75-85 ($p \leq .001$)
Visuospatial reasoning	8.95	4, 154	**< .001**	.19	18-28 > 65-85 ($p \leq .019$) 45-64 > 75-85 ($p \leq .006$)
Visual organization	12.32	4, 154	**< .001**	.24	18-74 > 75-85 ($p < .001$)
Vocabulary	13.36	4, 154	**< .001**	.30	18-28 < 45-85 ($p \leq .001$)
Processing speed					
Verbal processing speed	3.81	4, 154	**.006**	.09	18-54 > 75-85 ($p \leq .016$)
VS processing speed	9.60	4, 154	**< .001**	.20	18-28 > 55-85 ($p \leq .008$) 45-54 > 65-85 ($p \leq .013$) 55-64 > 75-85 ($p = .003$)
Short-term and working memory					
Verbal short-term memory	2.24	4, 154	*.067*	.05	—
Verbal working memory	1.96	4, 154	.102	.05	—
Visual short-term memory	11.65	4, 154	**< .001**	.23	18-28 > 45-85 ($p \leq .004$) 45-54 > 75-85 ($p = .046$)
Spatial short-term memory	8.46	4, 154	**< .001**	.25	18-28 > 55-85 ($p \leq .024$) 45-54 > 75-85 ($p \leq .009$)
Spatial working memory	10.65	4, 154	**< .001**	.22	18-28 > 55-85 ($p \leq .003$) 45-54 > 75-85 ($p = .003$)
Inhibitory control	34.82	4, 154	**< .001**	.47	18-28 > 45-85 ($p < .001$) 45-54 > 55-85 ($p \leq .025$) 55-64 > 75-85 ($p < .001$) 65-74 > 75-85 ($p = .010$)
Flexibility	11.66	4, 154	**< .001**	.27	18-54 > 55-85 ($p \leq .007$) 55-64 > 75-85 ($p = .001$)

Note. Years of formal education were entered as a covariate. Post-hoc group comparisons were conducted with Bonferroni correction. $N = 160$.

Visuospatial abilities and vocabulary knowledge. The percentages of correct responses in the visuospatial tasks (i.e., HVOT for visual organization; MRT for object mental rotation; MR for visuospatial reasoning; OPT for object-based perspective taking) and in the MHVT for vocabulary knowledge were calculated for each age group and are presented in Figure 10. The linear trend of the Age Group effect was significant for vocabulary knowledge and all visuospatial tasks ($p < .001$). Results (Table 25) showed that object-based mental rotation was significantly impaired in older adults aged 75-85 compared to adults aged between 18-28. Older individuals aged 75-85 performed worse than all other age groups in visual organization, indicating a sharper decline in advanced age. Visuospatial reasoning started to significantly decline from the mid-60s, while object-based perspective taking (requiring self-based mental rotation) started to decline as early as from the mid-50s. By contrast, vocabulary knowledge significantly increased from the mid-40s and continued to slowly rise until late adulthood.

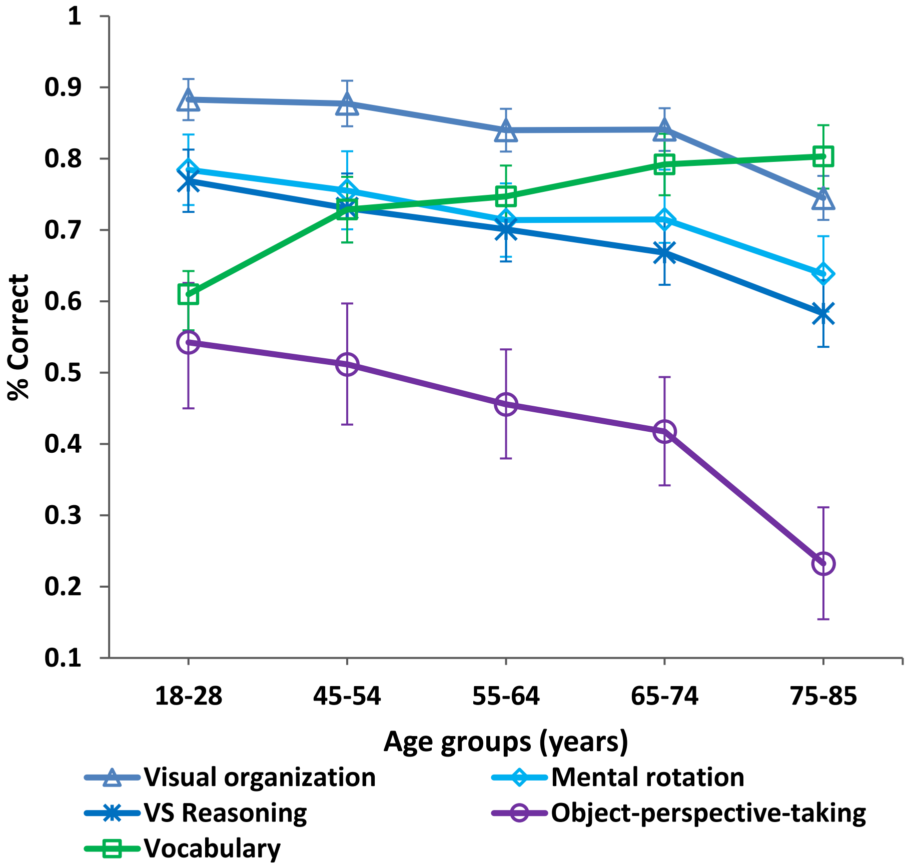


Figure 10. Visuospatial abilities and vocabulary knowledge across the adult life
Visual organization: HVOT; mental rotation: MRT; VS reasoning: MR; object-based perspective taking: OPT; vocabulary: MHVT; VS = visuospatial; Error bars represent 95% confidence intervals; $N = 160$.

The model also yielded a main effect of gender on mental rotation, $F(1, 149) = 10.89$, $p = .001$, $\eta^2_p = .07$, with males ($M = 77.10\%$, $SE = 1.80$) performing better than females ($M = 69.45\%$, $SE = 1.31$), independently of age. Gender significantly affected object-perspective taking performance, $F(1, 149) = 14.82$, $p < .001$, $\eta^2_p = .11$, with males ($M = 49.05\%$, $SE = 2.94$) performing better than females ($M = 34.50\%$, $SE = 2.36$), independently of age. No significant gender × age interaction effects were observed in any of the tasks considered.

Processing resources: Processing speed. Figure 11 presents the performance of each age group on the words (ST-W) and colours (ST-C) conditions of the Stroop task as measures of processing speed of verbal and visual information, respectively. The linear trend of the Age Group effect was significant for performance in the words and colours condition of the Stroop task ($p < .001$). According to the results (Table 25), processing speed of visual information significantly decreased as early as from the mid-50s, whereas processing speed of verbal information significantly decreased in a much later age, from the mid-70s.

Processing resources: Short-term and working memory. Figure 12 presents each age group's maximum short-term and working memory span for verbal (DS), visual (MPT), and spatial (SS) information. The analyses (Table 25) revealed domain-specific ageing effects on short-term and working memory resources. More specifically, age significantly influenced memory resources for visual and spatial information, but not for verbal information. Short-term visual memory span dropped sharply from the mid-40s and continued to decline thereafter. Spatial short-term and working memory span declined significantly from the mid-50s and continued to decrease steadily throughout the adult lifespan.

Processing resources: Inhibitory control and mental flexibility. Figure 13 presents inhibitory control (interference score; ST-CW) and mental flexibility (log-transformed time to complete; TMT-B) for each age group. Trend analysis indicated that the linear function of the Age Group effect on TMT-B and ST-CW performance was significant ($p < .001$). The results (Table 25) showed a steep decline of inhibitory control abilities from the mid-40s, which continued to decrease gradually until late adulthood. Mental flexibility declined mildly from the mid-50s and then more sharply from the mid-60s until late adulthood.

There were no gender effects or any significant interaction effects involving gender in any of the measures tapping processing resources.

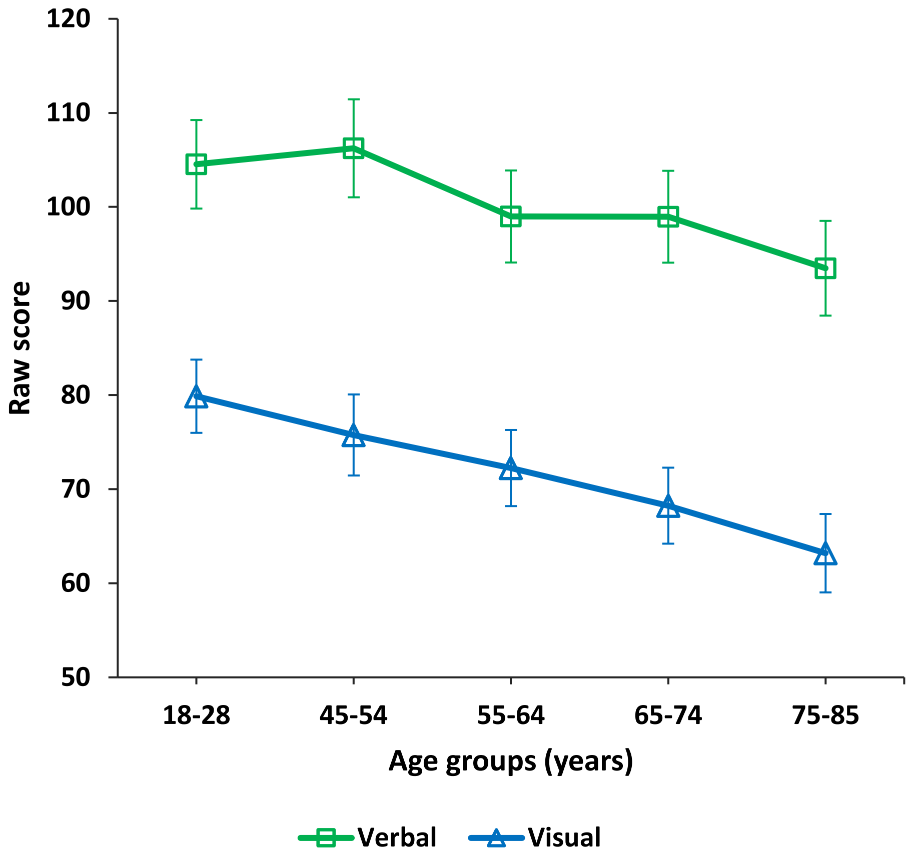


Figure 11. Processing speed of verbal (Stroop-W) and visual (Stroop-C) information across the adult lifespan.
Error bars represent 95% confidence intervals; *N* = 160.

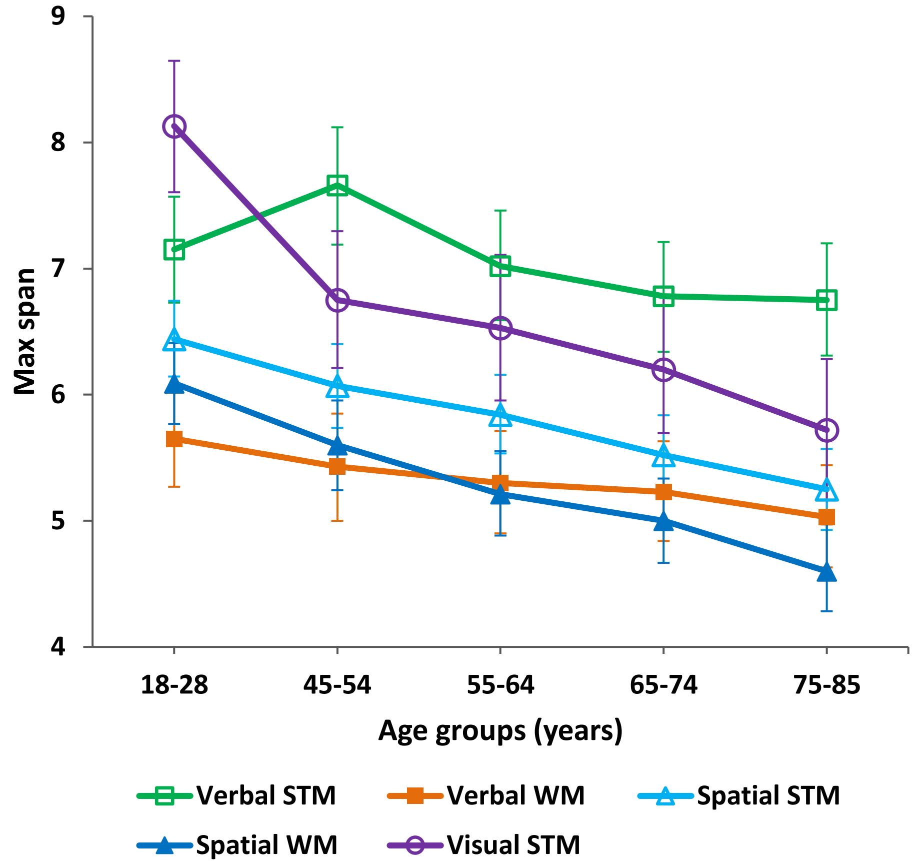


Figure 12. Short-term and working memory capacity for verbal (DS-F, DS-B), spatial (SS-F, SS-B), and visual (MPT) information across the adult lifespan.
STM = short-term memory; WM = working memory; Error bars represent 95% confidence intervals; *N* = 160.

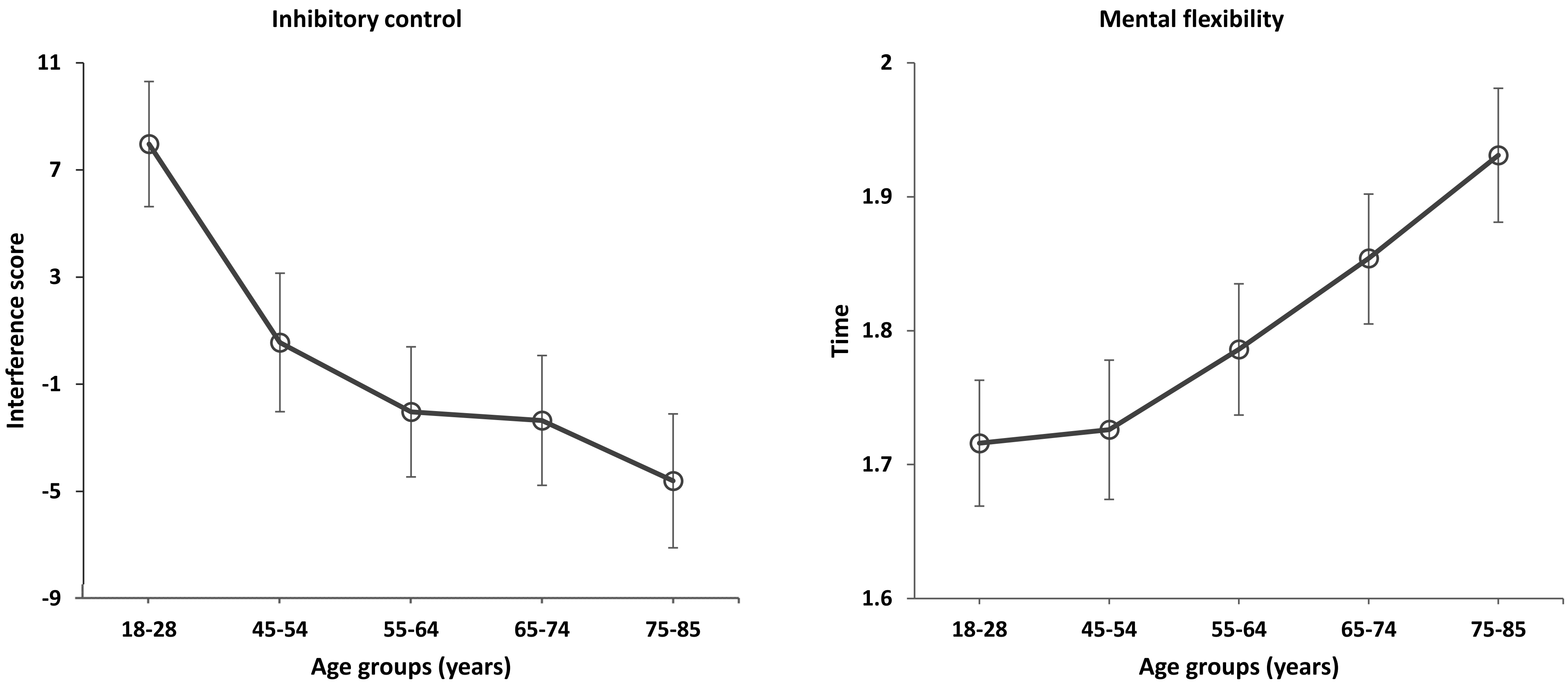


Figure 13. Inhibitory control (interference score, ST-CW; left panel) and mental flexibility (log-transformed time to complete, TMT-B; right panel) across the adult lifespan.
Error bars represent 95% confidence intervals; N = 160.

5.3.4.2 Verbal Comprehension in Spatial Reference Frames

Performance based on accuracy (proportion of correct responses) and speed (time to complete) for each age group across the self-centred, third-person-centred, object-centred, and environment-centred conditions of the Verbal Comprehension in Spatial Reference Frames task is presented in Figure 14.

Accuracy. The analysis resulted in a significant main effect of Age Group, $F(4, 154) = 6.43$, $p < .001$, partial $\eta^2 = .14$, with a significant linear trend ($p < .001$,) as well as a significant main effect of Reference Condition, $F(3, 462) = 14.33$, $p < .001$, partial $\eta^2 = .08$, on accuracy of performance in the VCSRF. Post-hoc pairwise comparisons with Bonferroni correction showed that comprehension in the environment-centred condition was significantly lower compared to all other conditions ($p < .001$), and that accuracy in the self-centred condition was higher compared to all other conditions ($p < .001$) (percentage of correct responses: self-centred: $M = 99.99\%$, $SE = .01$; third-person-centred: $M = 97.23\%$, $SE = .81$; object-centred: $M = 96.08\%$, $SE = 1.21$; environment-centred: $M = 81.19\%$, $SE = 2.27$). In addition, post-hoc group comparisons with Bonferroni correction revealed that, overall, the 75-85 age group performed less accurately than all other age groups in the VCSRF task ($p \leq .007$) (percentage of correct responses: 18-28: $M = 94.89\%$, $SE = 1.59$; 45-54: $M = 94.75\%$, $SE = 1.76$; 55-64: $M = 94.36\%$, $SE = 1.65$; 65-74: $M = 94.18\%$, $SE = 1.65$; 75-85: $M = 89.15\%$, $SE = 1.70$).

Furthermore, there was a significant Age Group × Reference Condition interaction, $F(12, 462) = 4.44$, $p < .001$, partial $\eta^2 = .11$. Simple effects analyses revealed that age significantly affected comprehension in the third-person-centred condition, $F(4, 154) = 4.02$, $p = .004$, partial $\eta^2 = .09$, and in the environment-centred condition, $F(4, 154) = 6.57$, $p < .001$, partial $\eta^2 = .14$, but not in the self-centred and object-centred conditions ($p > 250$). Bonferroni-corrected post-hoc comparisons indicated that the 75-85 age group performed significantly worse than all other age groups in the third-person-centred condition ($p \leq .050$), as well as in the environment-centred condition, ($p \leq .005$). No other group differences were noted (Figure 14).

These results point to differential age effects on verbal comprehension under different spatial reference frames. Processing within a self-centred and an object-centred reference frame remains well preserved throughout the adult lifespan, whereas processing in an third-person-centred and especially in an environment-centred spatial reference frame declines in late adulthood. Moreover, these results provide experimental evidence further confirming

Levinson's (1996) classification of coordinate systems that serve as spatial reference frames defining spatial relations between objects.

Speed. Speed scores for each condition of the VCSRF were logarithmically transformed to control for age differences in baseline performance. The advantage of this method is that the difference between log-transformed speed scores corresponds to proportional scores. Hence, age-by-condition interactions were interpreted on the basis of proportional scores and not on the basis of difference scores (cf. Meiran, 1996). A similar factorial analysis of covariance resulted in a main effect of Age Group, $F(4, 154) = 26.44$, $p < .001$, partial $\eta^2 = .41$, with a significant linear function of the effect ($p < .001$), as well as a significant main effect of Reference Condition, $F(3, 462) = 53.62$, $p < .001$, partial $\eta^2 = .26$, on the speed of performance in the VCRF. Pairwise comparisons showed that speed in the absolute condition was much slower compared to all other conditions ($p < .001$), and that the speed in the third-person-centred condition was slower than the speed in the self-centred ($p < .001$) and object-centred ($p < .001$) conditions, while speed of performance in the self-centred and object-centred conditions was at similar levels ($p > .250$) (time to complete: self-centred: $M = 1.73$, $SE = .004$; third-person-centred: $M = 1.76\%$, $SE = .005$; object-centred: $M = 1.73$, $SE = .005$; environment-centred: $M = 1.92$, $SE = .006$). Group comparisons with Bonferroni corrections showed that 65-74 and 75-85 age groups required significantly more time to complete the task conditions compared to participants in the 18-28, 45-54, and 55-64 age groups ($p \leq .024$) (time to complete: 18-28: $M = 1.73$, $SE = .01$; 45-54: $M = 1.76$, $SE = .01$; 55-64: $M = 1.77$, $SE = .009$; 65-74: $M = 1.81$, $SE = .009$; 75-85: $M = 1.85$, $SE = .009$). There was no significant Age Group × Reference Condition interaction effect, suggesting that the effect of Age Group on speed of performance was similar across the different conditions of the VCSRF task (Figure 14).

These results indicate that ageing has similar effects on the time required to process descriptions of spatial relations under different spatial reference frames. They also point that participants are much faster in processing descriptions of spatial relations within a relative self-centred and an object-centred reference frame, while they require more time within a third-person-centred reference frame, and even more within an environment-centred reference frame, confirming that allocentric spatial processing is more demanding.

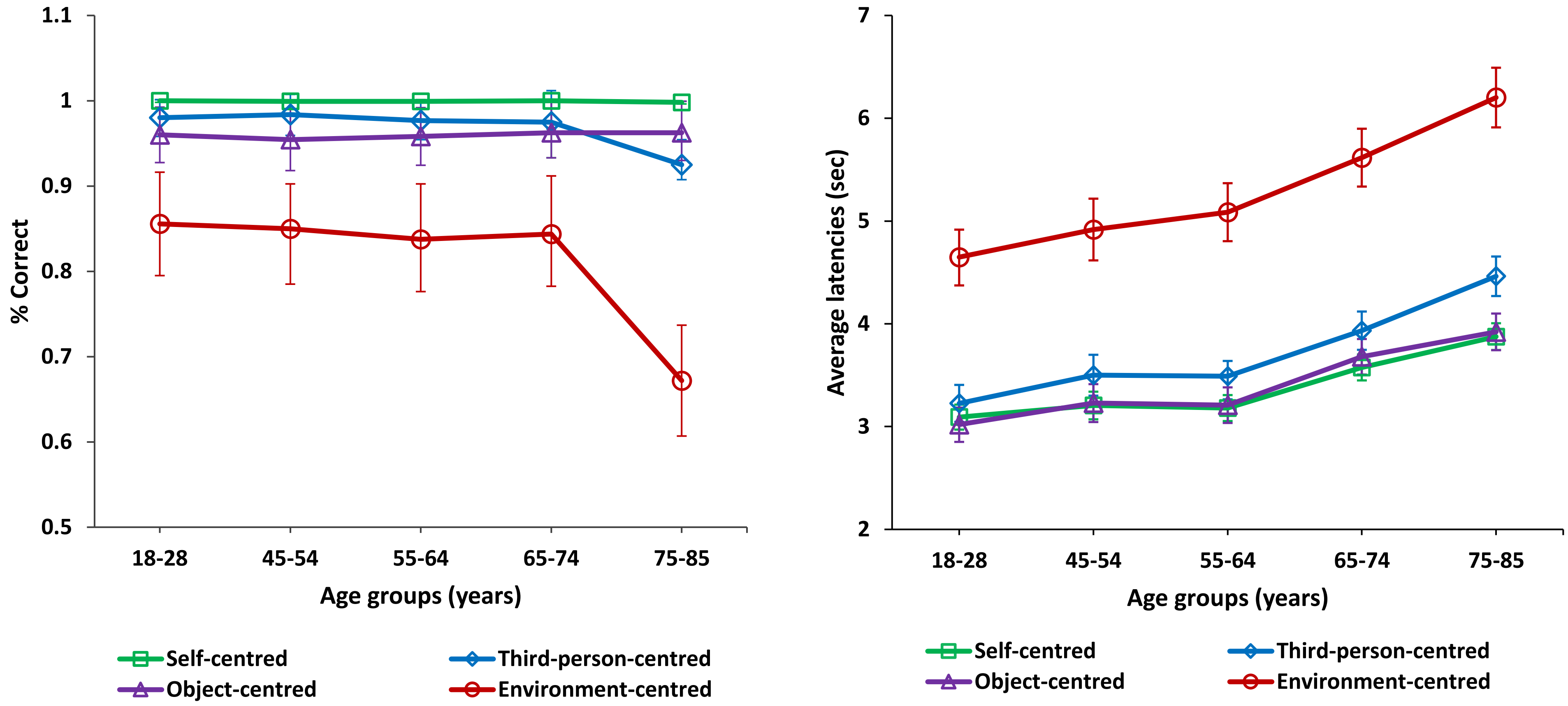


Figure 14. Performance based on accuracy (proportion of correct responses; left panel) and speed (average response latencies; right panel) under different spatial reference frames (Verbal Comprehension in Spatial Reference Frames task) across the adult lifespan.
Error bars represent 95% confidence intervals; *N* = 160.

5.3.4.3 Episodic memory

Performance based on the proportion of correctly recalled items in the immediate and delayed trials across the non-spatial verbal (Logical Memory subscale), route and survey spatial-verbal (Spatial Verbal Memory task), and non-verbal visuospatial (Rey-Osterrieth Complex Figure Test) memory tasks for all age groups is presented in Figure 15.

Immediate recall. Within each category, the percentages of correctly recalled items were calculated. A mixed 5 (Age Group) × 4 (Information Type: non-spatial verbal, route-based spatial-verbal, survey-based spatial-verbal, non-verbal visuospatial) ANCOVA (covariate: Education) revealed a significant main effect of Information Type, $F(3, 462) = 8.22$, $p < .001$, partial $\eta^2 = .05$, on immediate recall. Pairwise comparisons with Bonferroni correction revealed that recall for survey-based spatial information was poorer than recall for non-spatial verbal information and recall for route-based spatial descriptions ($p < .001$), and that recall for route descriptions was poorer than recall for non-spatial verbal information ($p < .001$). Moreover, non-verbal visuospatial recall was higher than recall for all other types of information ($p < .001$) (non-spatial verbal: $M = 61.25\%$, $SE = 2.65$; route-based spatial-verbal: $M = 47.72\%$, $SE = 2.78$; survey-based spatial-verbal: $M = 40.76\%$, $SE = 3.00$; non-verbal visuospatial: $M = 73.66\%$, $SE = 4.28$).

There was also a significant main effect of Age Group, $F(4, 154) = 6.86$, $p < .001$, partial $\eta^2 = .15$, with trend analysis revealing that only the linear function of the effect was significant ($p < .001$). Post-hoc group comparisons with Bonferroni correction indicated that the 18-28 age group outperformed the 65-74 ($p = .021$) and 75-85 ($p < .001$) age groups. Moreover, the 45-54 age group performed better than the 75-85 age group ($p = .001$) and the 65-74 age group, although the latter did not reach significance ($p = .081$) (percentage of immediate memory recall: 18-28: $M = 63.71\%$, $SE = 4.94$; 45-54: $M = 62.89\%$, $SE = 5.47$; 55-64: $M = 57.65\%$, $SE = 5.14$; 65-74: $M = 55.24\%$, $SE = 5.13$; 75-85: $M = 51.01\%$, $SE = 5.29$). However, there was no significant Age Group × Information Type interaction effect ($p = .094$), although the linear trend of the interaction tended to reach significance ($p = .07$) (Figure 15).

These results suggest that ageing has similar effects on immediate episodic memory for different types of information, including verbal memory for spatial information presented from a route or a survey perspective, memory for (non-spatial) verbal information, and for (non-verbal) visuospatial information.

Delayed recall. A similar mixed analysis of covariance resulted in a significant main effect of Information Type, $F(3, 462) = 10.87$, $p < .001$, partial $\eta^2 = .06$, on the delayed memory recall. As in the immediate trials, post-hoc analyses with Bonferroni correction revealed that delayed recall for survey descriptions was lower than recall for route descriptions and for non-spatial verbal information ($p < .001$), and that recall for route descriptions was poorer than verbal recall with no spatial information ($p < .001$). Again, delayed recall for non-verbal visuospatial information was higher than recall for all other types of information ($p < .001$) for all participants (non-spatial verbal: M = 52.11%, SE = 2.77; route-based spatial-verbal: M = 43.34%, SE = 2.93; survey-based spatial-verbal: M = 38.68%, SE = 2.84; non-verbal visuospatial: M = 71.85%, SE = 4.39).

There was also a significant main effect of Age Group, $F(4, 154) = 7.20$, $p < .001$, partial $\eta^2 = .16$, with a significant linear trend ($p < .001$), which was qualified by a significant Age Group × Information Type interaction effect, $F(12, 462) = 1.95$, $p = .028$, partial $\eta^2 = .05$. Follow-up simple effects tests showed that the effect of age on delayed recall was significant for the route, $F(4, 154) = 3.47$, $p = .010$, $\eta^2 = .08$, and the survey, $F(4, 154) = 4.82$, $p = .001$, $\eta^2 = .11$, spatial-verbal memory, as well as for the non-verbal visuospatial memory, $F(4, 154) = 5.56$, $p < .001$, $\eta^2 = .12$, but not for the non-spatial verbal memory ($p = .089$). Pairwise comparisons with Bonferroni correction indicated that the 65-74 and 75-85 age groups recalled less information than the 18-28 age group in the route spatial-verbal task ($p \leq .050$), and less information than both 18-28 and 45-54 age groups in the survey spatial-verbal task ($p \leq .050$). In addition, the 75-85 age group had a poorer recall for non-verbal visuospatial information when compared to individuals aged between 18-28, 45-54, and 55-64 ($p \leq .008$) (Figure 15).

Contrary to the results of the immediate recall trials, these findings point to significant discrepancies amongst the adult lifespan trajectories of long-term episodic memory, depending on the type of information. Spatial-verbal memory from either a route or a survey perspective is stable until early midlife, begins to mildly drop in later midlife, and declines substantially in the mid-60s. Non-verbal visuospatial memory declines only mildly after late midlife until the late adulthood, when it deteriorates sharply. On the other hand, the changes in non-spatial verbal episodic memory are particularly mild across the adult lifespan.

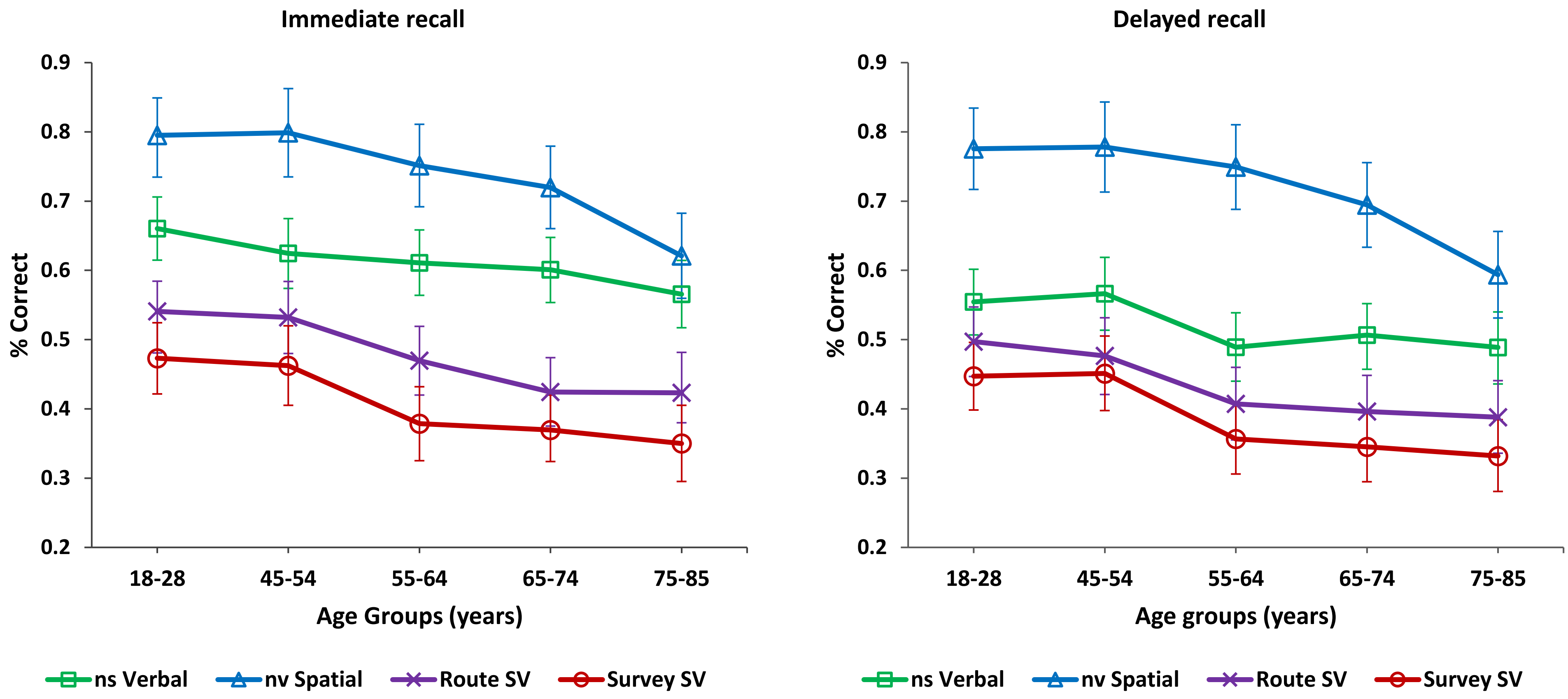


Figure 15. Episodic memory for non-spatial verbal (LM), route-based and survey-based spatial-verbal (Spatial Verbal Memory task), and non-verbal visuospatial (ROCF) information across the adult lifespan.
Left panel: immediate recall; right panel: delayed recall; span. ns = non-spatial, SV = spatial-verbal, nv = non-verbal. Error bars represent 95% confidence intervals; *N* = 160.

5.3.4.4 Naming

Performance based on naming accuracy (proportion of correct responses) and naming speed (time to complete) across all conditions [static (SNT-S) and dynamic (SNT-D) spatial relations; objects (BNT); actions (ANT)] for all age groups is presented in Figure 16.

Naming accuracy. Within each category, the percentages of correctly named items were calculated. A mixed 5 (Age Group) × 4 (Naming Category: static spatial relations, dynamic spatial relations, objects, actions) ANCOVA (covariate: Education) revealed a significant main effect of Age Group, $F(4, 154) = 5.45$, $p < .001$, partial $\eta^2 = .12$, with trend analysis revealing a significant linear trend of the effect ($p < .001$), as well as significant main effect of Naming Category, $F(3, 462) = 288.26$, $p < .001$, partial $\eta^2 = .65$, on naming accuracy. Post-hoc pairwise comparisons with Bonferroni correction revealed that naming accuracy for both static and dynamic spatial relations was significantly lower than for objects and actions ($p < .001$), and that naming accuracy for objects was lower than for actions ($p < .001$), for all participants (naming accuracy for static spatial relations: $M = 86.72\%$, $SE = .86$; dynamic spatial relations: $M = 88.01\%$, $SE = .93$; objects: $M = 89.91$, $SE = 1.08$; actions: $M = 96.27$, $SE = .93$).

We also found a significant Age × Category interaction effect on naming accuracy, $F(12, 462) = 2.87$, $p = .001$, partial $\eta^2 = .07$. Analyses of simple main effects showed that the effect of Age Group on naming accuracy was significant for static, $F(4, 154) = 7.62$, $p < .001$, and dynamic, $F(4, 154) = 16.11$, $p < .001$, spatial relations, as well as for objects, $F(4, 154) = 2.87$, $p = .025$, but not for actions ($p = .083$). Bonferroni-corrected pairwise comparisons in each naming condition indicated that the 75-85 group was less accurate in naming static spatial relations compared to the younger (18-28; $p = .019$) and middle aged (45-54 and 55-64; $p \leq .001$) groups, while the discrepancy between the 75-85 and 65-74 groups tended but did not reach significance ($p = .072$). Moreover, the 65-74 and 75-85 age groups were less accurate in naming dynamic spatial relations compared to younger (18-28; $p \leq .036$) and middle aged (45-54 and 55-64; $p \leq .033$) groups. In naming accuracy for objects, the 45-54 age group performed significantly better than the 18-28 group ($p = .037$), while no other significant differences were revealed between the age groups (Figure 16; left panel).

These results reveal for the first time differential effects of increasing age on naming abilities for diverse lexical-semantic categories. On the one hand, object naming slightly improves in midlife and remains intact until late adulthood, while action naming remains stable throughout the adult lifespan. On the other hand, ageing has a negative impact on naming spatial relations between objects. More specifically, naming static spatial relations remains relatively stable until the mid-60s, and declines sharply in the mid-70s, while the ability to accurately describe dynamic spatial relations starts to mildly drop from the mid-50s and begins to significantly decline from the mid-60s.

Naming speed. A similar mixed model of ANCOVA revealed a significant main effect of Age Group, $F(4, 154) = 25.47$, $p < .001$, partial $\eta^2 = .40$, with a significant linear trend ($p < .001$), as well as a significant effect of Naming Category, $F(3, 462) = 4.37$, $p = .005$, partial $\eta^2 = .03$, on naming speed. Post-hoc comparisons indicated that naming static spatial relations was significantly slower than naming dynamic spatial relations ($p < .001$) and actions ($p < .001$), and that naming objects was significantly slower than naming actions ($p < .001$) and tended to be slower than naming dynamic spatial relations ($p = .060$) (naming speed for static spatial relations: $M = 2.03$, $SE = .008$; dynamic spatial relations: $M = 1.94$, $SE = .007$; objects: $M = 2.02$, $SE = .008$; actions: $M = 1.92$, $SE = .005$).

There was also a significant Age × Category interaction effect, $F(12, 462) = 5.38$, $p < .001$, partial $\eta^2 = .12$. Follow-up simple effects analyses revealed that age significantly affected naming speed in all conditions [static spatial relations: $F(4, 154) = 20.51$, $p < .001$, partial $\eta^2 = .35$; dynamic spatial relations: $F(4, 154) = 16.48$, $p < .001$, partial $\eta^2 = .30$; objects: $F(4, 154) = 17.23$, $p < .001$, partial $\eta^2 = .31$; actions: $F(4, 154) = 16.72$, $p < .001$, partial $\eta^2 = .30$]. Bonferroni-corrected pairwise comparisons for naming static spatial relations revealed significant differences between younger adults (18-28) and adults aged between 55 and 85 ($p < .001$), and a trend towards significant difference with the younger middle-aged adults ($p = .069$). Similarly, in naming dynamic spatial relations, younger adults (18-28) were significantly faster than adults aged between 55 and 85 ($p < .001$). In object naming, the 18-28 age group was significantly faster than the 75-85 age group ($p < .001$) but not than the rest of the age groups ($p > .250$), while the 45-54 age group was faster than the 65-74 ($p = .012$) and the 75-85 ($p < .001$) age groups. Moreover, the 65-74 group was significantly faster than the 75-85 group ($p < .001$). In naming speed for actions, the 18-28 age group was faster than the 65-74 and 75-85 age groups ($p \leq .011$), while the 45-54 age group was faster than adults aged between 55 and 85 ($p \leq .019$; Figure 16, right panel).

Overall, these results indicate a steady linear decrease on the speed of naming static and dynamic spatial relations with increasing age. Meanwhile, speed of lexical retrieval for object and action names significantly drops from the mid-60s and further decreases in late adulthood.

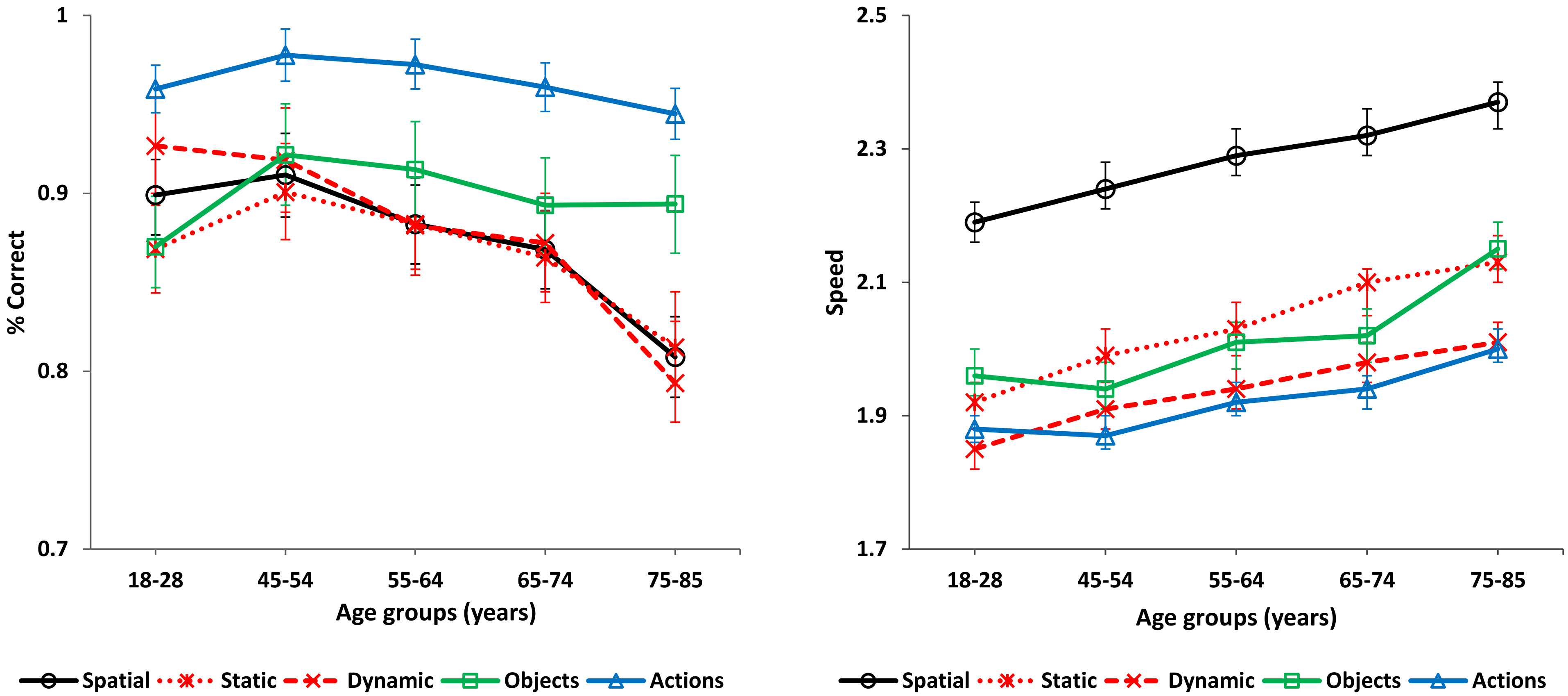


Figure 16. Naming accuracy (% correct; left panel) and speed (log-transformed time to complete; right panel) for spatial relations (Spatial Naming Test), objects (Boston Naming Test), and actions (Action Naming Test), across the adult life span.
Scores for spatial relations are presented separately for static and dynamic spatial relations, as well as composite scores. Error bars represent 95% confidence intervals; N = 160.

5.3.4.5 Verbal fluency

The mean score of correct words produced by each age group in each fluency condition (semantic categories: *spatial words*, *animals*, *actions*; phonemic categories: *F*, *A*, *S*) is presented in Figure 17. For the phonemic trials, a composite score was calculated by adding the number of correctly generated words starting from the letters *F*, *A*, and *S* and subsequently dividing the sum by three.

A factorial 5 (Age Group) × 4 (Fluency Category: *spatial words*, *animals*, *actions*, *phonemic*) ANCOVA (covariate: Education) revealed a significant main effect of Category on the number of generated words in the verbal fluency task, $F(3, 462) = 5.94$, $p = .001$, partial $\eta^2 = .04$. According to Bonferroni-adjusted post-hoc comparisons, participants generated more words in the animals semantic condition compared to all other fluency conditions ($p < .001$), while the number of words generated in the spatial-verbal and the phonemic conditions were at similar levels ($p > .250$), which were smaller compared to the number of words generated in the action semantic category ($p < .001$) (spatial words: M = 13.20, SE = .36; animals: M = 23.31, SE = .50; actions: M = 18.51, SE = .43; phonemic: M = 14.12, SE = .31). There was also a significant main effect of Age Group on verbal fluency performance, $F(4, 154) = 4.53$, $p = .002$, partial $\eta^2 = .11$, with only the linear function of the effect being significant ($p < .001$), which was qualified by a significant Age × Condition interaction effect, $F(12, 462) = 1.89$, $p = .033$, partial $\eta^2 = .05$. Analyses of simple main effects showed that the effect of Age Group on verbal fluency performance was significant for spatial words, $F(4, 154) = 2.67$, $p = .041$, partial $\eta^2 = .06$, animals, $F(4, 154) = 2.75$, $p = .030$, partial $\eta^2 = .07$, and actions, $F(4, 154) = 5.37$, $p < .001$, partial $\eta^2 = .12$, but not for the phonemic condition ($p > .250$). Group comparisons with Bonferroni correction showed that the 45-54 group performed better than the 75-85 group in the categories animals ($p = .033$) and spatial words ($p = .043$). In the actions category, both the 18-28 and 45-54 groups performed significantly better than the 75-85 group ($p \leq .003$), and, additionally, the 45-54 group tended to perform better than the 65-74 group, but the difference did not reach statistical significance ($p = .056$) (Figure 10).

Overall, these results indicate that word production according to semantic cues (i.e., *animals*, *actions*, *spatial words*) declines in advanced age, while ageing does not affect word production based on phonemic cues (i.e., words begging from *F*, *A*, and *S*). In all semantic conditions, younger middle-aged adults (aged between 45-54) achieved the highest performance and older-older adults (aged between 75-85) the poorest. This suggests that the adult-lifespan trajectory of spatial-verbal fluency is similar to the trajectories of other types of semantic fluency, indicating a common pattern for semantically-cued word production, independent of the differences in the word classes involved (i.e., nouns in the *animal* condition, verbs in the *action* condition, and spatial prepositions in the *spatial words* condition). Nevertheless, the decline in the actions semantic condition seems to be steeper than the decline in other types of semantic verbal fluency (see also Section 5.3.5).

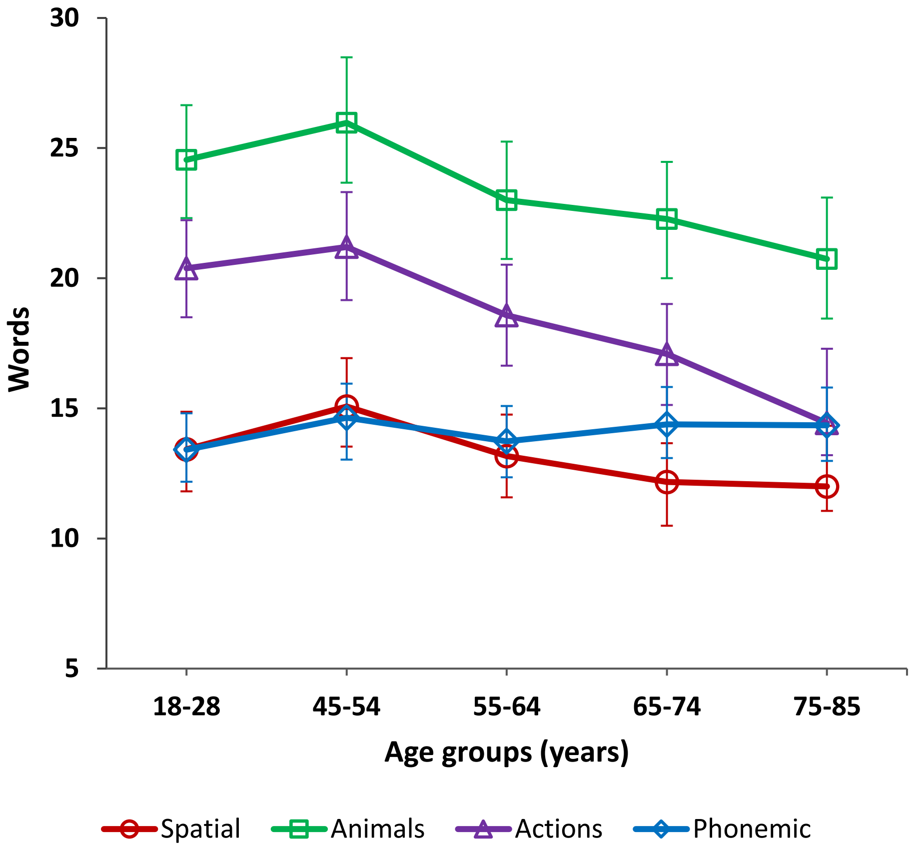


Figure 17. Semantic (*spatial words*, *animals*, and *actions*) and phonemic (words beginning from *F*, *A*, and *S*) verbal fluency performance across the adult lifespan.
A composite score from *F*, *A*, and *S* trials was calculated for the phonemic condition. Error bars represent 95% confidence intervals; $N = 160$.

5.3.5 Overlaps and discrepancies on adult-lifespan cognitive trajectories

As mentioned earlier, one of the main objectives of the present studies was to compare the adult-lifespan trajectories of spatial-verbal abilities against other cognitive measures. Therefore, the question of whether the age-dependent changes are similar or different across the different cognitive domains was further examined with a series of regression analyses. First, participants' performance based on accuracy scores on all measures was transformed into standardized *z*-scores to facilitate comparisons across variables. The 95% confidence intervals of regression analyses were compared for the slopes and intercepts for each measure, using the linear trend of age (in years) as the predictor variable. Based on the results of the trend analyses in the previous section (5.3.4), which revealed significant linear effects of age on all measures, the quadratic (which explained only a marginal part of the variance in naming accuracy) and the cubic (which were not significant) effects of age were disregarded. For each comparison, half of the average of the overlapping confidence intervals was calculated and added to the lower bound estimate of the first slope, and then we examined whether the upper bound estimate of the second slope would exceed that value; if the confidence intervals overlapped by less than 50%, the slopes were considered significantly different from each other (Cumming, 2009). The results of these analyses are presented in Table 26.

These comparisons revealed a number of overlaps and discrepancies across the adult lifespan trajectories of different aspects of cognition. The slopes for semantic verbal fluency were partially overlapping, although the decline was steeper for action verbal fluency, while they were substantially different from phonemic verbal fluency (Δb = -.011 to -.019; $p < .050$). In naming accuracy, the results confirmed that the difference between the slopes for spatial relations and objects (Δb = -.022) and between the slopes for spatial relations and actions (Δb = -.024) were significantly different ($p < .050$), with the slope of spatial naming being steeper than the slopes of object and action naming. Regarding episodic memory, the slopes for route-based spatial-verbal memory, survey-based spatial-verbal memory, and non-verbal spatial memory were identical, and they were all significantly different from the slope for non-spatial verbal memory (Δb = -.024; $p < .050$). There was a substantial overlap amongst visuospatial measures, except for object-perspective taking (OPT) where the slope was steeper compared to the slopes for the other visuospatial measures (Δb = -.022 to -.027; $p < .050$).

Table 26. *Comparing Regressions of Performance across all Measures with Age*

Measure (*task*)	Slope	Slope SE	Intercept	Intercept SE	R^2	Bonferroni's CIs for slope LL	UL
Naming							
Spatial relations (SNT)	-.019	.003	1.040	.18	.15**	-.026	-.013
Objects (BNT)	.003	.004	-.156	.25	.01	-.005	.011
Actions (ANT)	-.005	.004	.290	.23	.01	-.013	.002
Episodic memory							
Route SV (SVM-R)	-.015	.004	.805	.22	.09**	-.022	-.007
Survey SV (SVM-S)	-.015	.004	.840	.20	.10**	-.022	-.009
(non-Sp) Verbal (LM)	-.009	.004	.519	.25	.04*	-.017	-.002
(non-Ver) VS (ROCF)	-.015	.004	.857	.20	.10**	-.023	-.007
Verbal fluency							
Spatial	-.008	.003	.436	.20	.03*	-.014	-.002
Animals	-.011	.004	.615	.21	.05**	-.019	-.004
Actions	-.016	.004	.883	.20	.10**	-.023	-.010
Phonemic (FAS)	.003	.004	-.161	.19	.01	-.004	.010
Verbal Comprehension in Spatial Reference Frames (VCSRF)							
Self-centred	-----				.00		
Third-person-centred	-.009	.005	.485	.22	.03*	-.017	-.001
Object-centred	-.001	.004	.052	.23	.00	-.007	.006
Environment-centred	-.012	.004	.672	.19	.06**	-.020	-.006
Visuospatial abilities							
Mental rotation (MRT)	-.015	.003	.824	.19	.10**	-.022	-.008
Object-perspective taking (OPT)	-.042	.007	2.707	.50	.21**	-.056	-.025
Visual organization (HVOT)	-.020	.003	1.123	.16	.17**	-.027	-.015
VS reasoning (MR)	-.021	.003	1.155	.18	.18**	-.028	-.015
Vocabulary (MHVT)	.023	.003	-1.281	.18	.23**	.017	.029
Processing Speed							
Verbal PS (ST-N)	-.014	.004	.760	.23	.08**	-.021	-.006
VS PS (ST-C)	-.023	.004	1.257	.24	.22**	-.031	-.015
Inhibition (ST-CN)	-.034	.003	1.895	.20	.50**	-.040	-.028
Flexibility (TMT-B)	-.022	.004	1.224	.18	.21**	-.015	-.029
Short-term and working memory							
Verbal STM (DS-F)	-.005	.004	.257	.22	.01	-.012	-.003
Verbal WM (DS-B)	-.012	.004	.640	.22	.06**	-.020	-.005
Visual STM (MPT)	-.024	.004	1.338	.23	.25**	-.031	-.018
VS STM (SS-F)	-.025	.004	1.363	.23	.26**	-.032	-.017
VS WM (SS-B)	-.023	.004	1.265	.22	.23**	-.030	-.015

Note. Only the linear function of the regression model is presented. Bonferroni confidence intervals (CIs) are based on $\alpha = .05$ for the family of comparisons. LL = lower confidence interval; UL = upper confidence interval; VS = visuospatial; STM = short-term memory; WM = working memory; $N = 160$; $*p < .010$, $**p < .001$.

Moreover, there were significant discrepancies in processing resources measures depending on the nature of the material: the slopes for visual and visuospatial short-term and working memory measures were far steeper than those for verbal material (Δb = -.012 to -.020; $p < .050$), and similarly, the slope for processing speed for visual information was steeper than for verbal information (Δb = -.010; $p < .050$). Finally, the slope for inhibitory control (interference score in the ST-CW) was mildly steeper than for flexibility (Δb = -.012; $p < .050$).

These findings provide striking evidence of contrasting lifespan trajectories amongst different cognitive abilities. Our novel findings indicate a clear distinctiveness in the developmental trajectories of spatial-verbal and non-spatial verbal abilities across the adult lifespan, with evidence in favour of a larger age-related change in spatial-verbal abilities. The adult-lifespan trajectories of different aspects of spatial language processing are comparable to the trajectories of visuospatial abilities and substantially different from the trajectories of verbal abilities, except for verbal fluency. Overall, our results suggest that the rate of cognitive decline is dependent on the nature of the material (verbal vs visuospatial), pointing to a larger age-related decline in the visuospatial and spatial-verbal domain compared to the non-spatial verbal domain.

5.3.6 Adult-lifespan relationships among measures

In order to examine whether the relationships amongst different measures change across the adult lifespan, a series of correlational analyses were computed for each age group separately. Subsequently, a series of comparisons of correlation coefficients were conducted using Fisher's *z* transformation of *r* (Weaver & Wuensch, 2013). The results of these analyses are presented in Table 27 and in the following sections for each novel spatial language task separately.

Table 27. *Pearson Correlations Between Variables Stratified by Age Group*

Measure	Age group (years)				
	18-28	45-54	55-64	65-74	75-85
Spatial verbal fluency					
Visuospatial reasoning	.427*	.239	.326	.154	.507**
Vocabulary knowledge	.026	.245	.216	.359*	.358*
Spatial naming					
Visuospatial reasoning	.373*	.598**	.321	.346*	.399*
Vocabulary knowledge	.015	.218	.325	.181	.555*
Route-based spatial verbal memory					
(non-verbal) VS memory	.362*	.383*	.391*	.092	.217
(non-spatial) Verbal memory	.445**	.625**	.511**	.357*	.602**
Survey-based spatial verbal memory					
(non-verbal) VS memory	.433*	.268	.348*	.103	.228
(non-spatial) Verbal memory	.188	.463*	.489**	.450*	.472**
VC in spatial reference frames					
VS reasoning	.579**	.486**	.223	.377*	.488**
Mental flexibility	-.031	-.254	.119	-.513**	-.576**

Note. VS = visuospatial reasoning; VC = verbal comprehension. $N = 160$;
*$p \leq .010$; **$p \leq .001$.

5.3.6.1 Spatial verbal fluency

A series of correlational analyses between performance on spatial verbal fluency and measures of visuospatial (MR) and verbal (MHVT) intelligence, respectively, were conducted for every age group (Figure 18; Table 27). The relationship between spatial verbal fluency and visuospatial reasoning (MR) did not change across the adult lifespan ($Z = 1.17$ to $-.40$, $p \geq .121$). On the other hand, the relationship between spatial verbal fluency and vocabulary knowledge (MHVT) changed substantially throughout the adult lifespan: the relation was non-significant during young adulthood, whereas for adults aged 65 or more, better vocabulary knowledge was associated with better performance in the spatial verbal fluency task ($Z = -1.92$ to -1.93, $p = .053$).

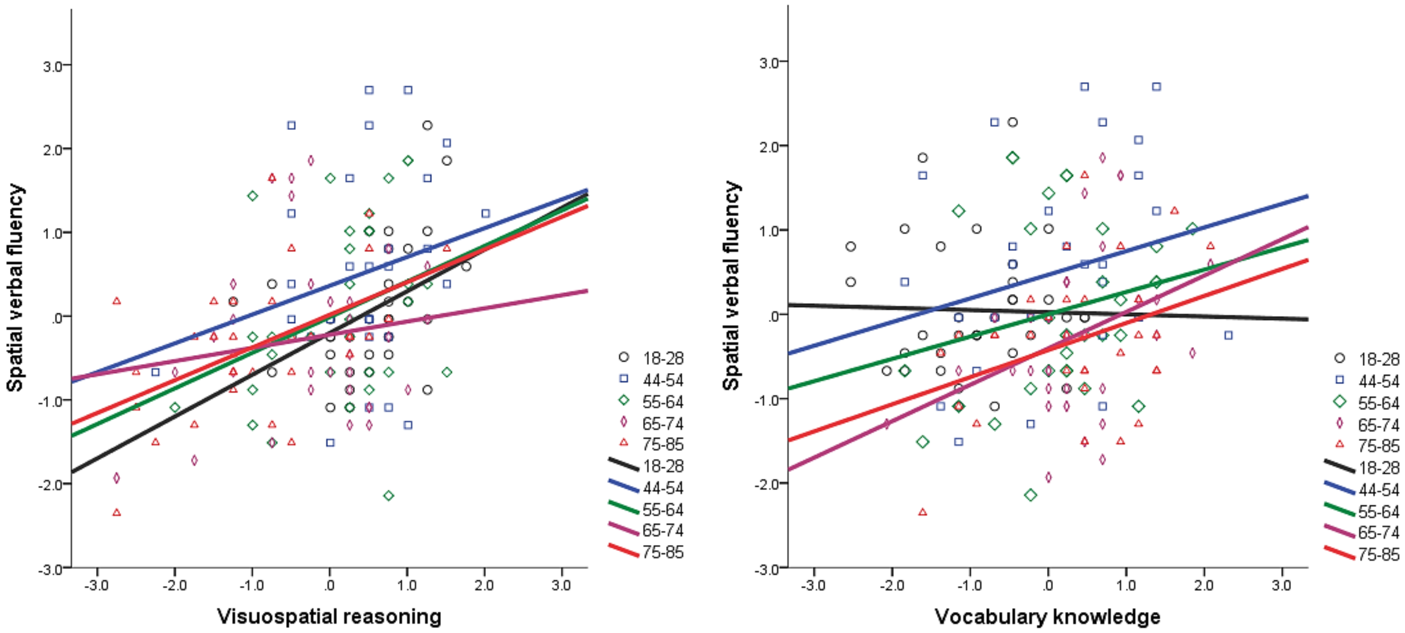


Figure 18. Correlations between spatial verbal fluency (SVF) and visuospatial reasoning (MR; left panel) and vocabulary knowledge (MHVT; right panel) across the adult life span. The lines show the regression for each relationship across the age groups. Readers are recommended to view this figure in colour.

5.3.6.2 Spatial naming

A series of correlational analyses between accuracy of performance on the spatial naming test and performance on the measures of visuospatial (MR) and verbal (MHVT) intelligence, respectively, were conducted for each age group (Figure 19; Table 27). The relationship between spatial naming accuracy and visuospatial reasoning (MR) did not change across the adult lifespan (Z = .12 to 1.50, $p \geq .133$), with higher performance in MR associated with higher spatial naming accuracy for all age groups. By contrast, there was a considerable age-related change in the relationship between spatial naming and vocabulary knowledge: there was no correlation between the two measures during young adulthood whilst they were highly positively correlated during late adulthood (Z = -2.36, p = .018), indicating that richer vocabulary in old age (75-85) is associated with more accurate naming abilities for spatial relations.

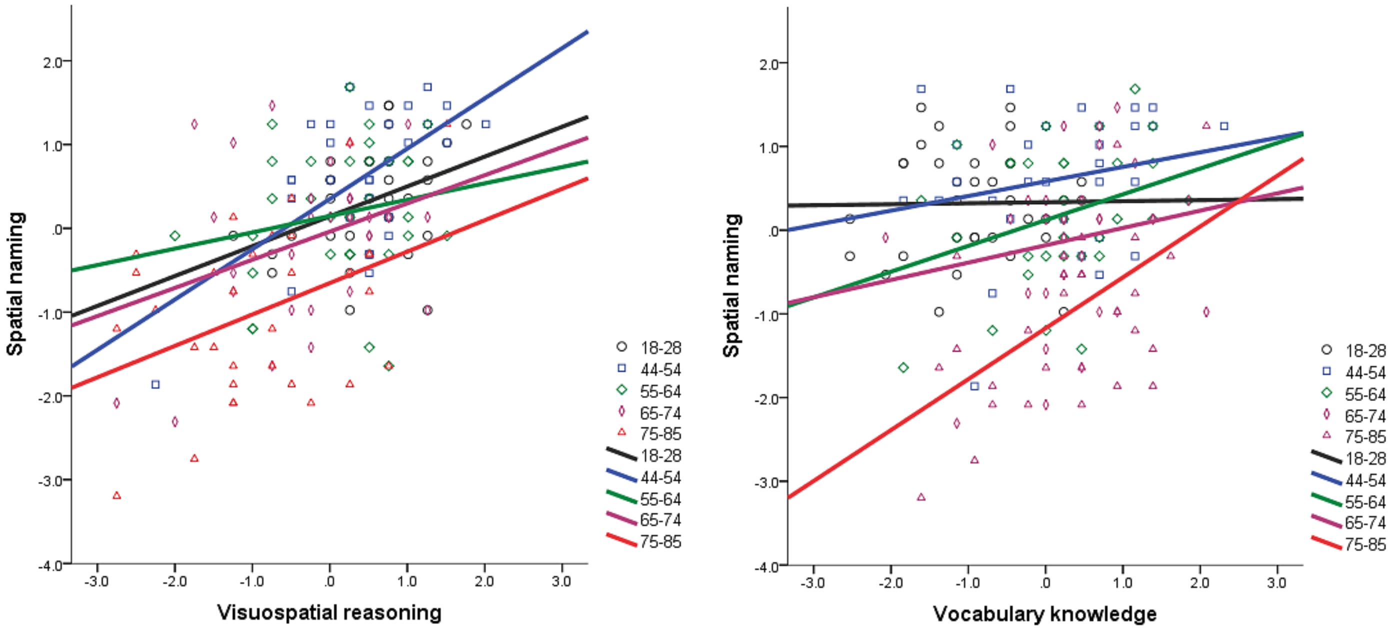


Figure 19. Spatial naming accuracy (% correct in the SNT) plotted against visuospatial reasoning (% correct in the MR; left panel) and vocabulary knowledge (% correct in the MHVT; right panel) for all age groups. The lines show the regression for each relationship across the age groups. Readers are recommended to view this figure in colour.

5.3.6.3 Spatial-verbal memory

A series of correlational analyses were conducted between the delayed recall trials of the route-based (Figure 20) and survey-based (Figure 21) conditions of the spatial-verbal memory task, and the delayed recall trials of the non-verbal visuospatial (ROCF) and non-spatial verbal (LM) memory tasks, respectively, for all age groups (Table 27).

Route. In all age groups, better (non-spatial) verbal episodic recall was associated with higher capacity to maintain verbal information for spatial relations presented from a route perspective, with the correlation between the two recall trials remaining relatively stable across the adult lifespan (Z = -1.25 to .14, $p \geq .211$). On the other hand, route-based spatial-verbal memory and (non-verbal) visuospatial memory were positively correlated throughout young and middle adulthood, whereas the correlation was non-significant during older adulthood; nevertheless, these correlations were not significantly different (Z = .62 to 1.23, $p \geq .207$).

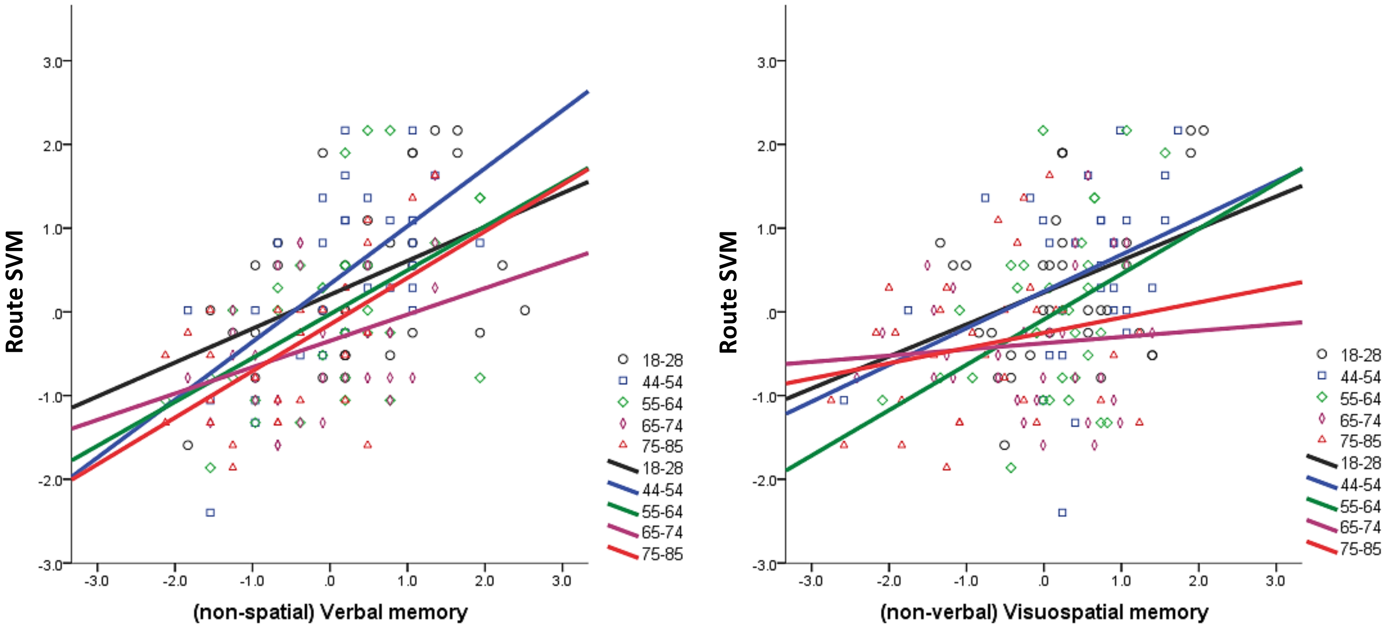


Figure 20. Correlations between route-based spatial-verbal memory (SVM-R) and (non-spatial) verbal memory (LM, left panel) and (non-verbal) visuospatial memory (ROCF), across the adult life span.

Survey. Results revealed similar to the route-based spatial-verbal memory (SVM-R) adult-lifespan patterns for the relationships between survey spatial-verbal (SVM-S) and non-spatial verbal memory (LM) versus survey spatial-verbal and non-verbal visuospatial (ROCF) memory tasks (Table 27; Figure 21). Overall, the correlations of SVM-S with LM and ROCF, respectively, were not statistically different across the age groups (SVM-S and LM: Z = -1.36 to .09, $p \geq .173$; SVM-S and ROCF: Z = -.09 to 1.42, $p \geq .155$). Nevertheless, it is worth mentioning that delayed (non-spatial) verbal memory capacity was positively related to delayed recall for survey descriptions amongst middle-aged (45-64) and older adults (65-85), but not in younger adults (18-28). In contrast, delayed (non-verbal) visuospatial memory capacity was positively related to delayed recall for survey descriptions amongst younger (aged between 18 and 28) and middle-aged adults (aged between 45 and 64), but not in older adults aged between 65 and 85.

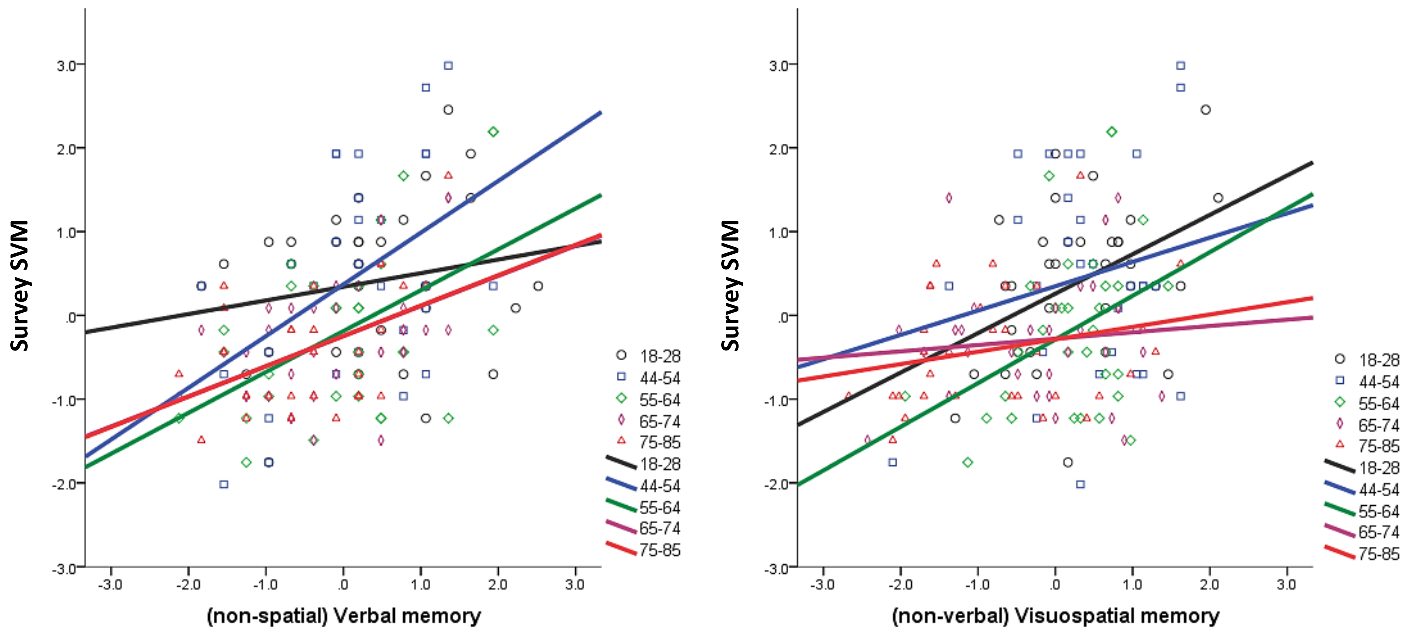


Figure 21. Correlations between survey-based spatial verbal memory (SVM-S) and (non-spatial) verbal memory (LM, left panel) and (non-verbal) visuospatial memory (ROCF), across the adult life span.

5.3.6.4 Verbal comprehension in spatial reference frames

A series of correlational analyses were conducted between a composite accuracy score in the VCSRF task and visuospatial reasoning (MR) and mental flexibility (TMT-B), respectively, for all age groups (Figure 22; Table 27). Results showed that visuospatial reasoning abilities were positively correlated with processing spatial descriptions under different spatial frames of reference in all age groups, with the relationship between the two measures remaining relatively stable across the adult-lifespan (Z = .50 to 1.71, $p \geq .087$). The relationship between processing spatial descriptions under different spatial frames of reference and mental flexibility, however, changed substantially throughout the adult-lifespan: the relation was non-significant during young adulthood but the two measures were strongly correlated in older adults aged between 65 and 85 (Z = 2.11 to 2.46, p = .013 to .034). These findings are indicating a significant association between poorer mental flexibility and poorer comprehension of spatial descriptions under different spatial reference frame amongst older individuals.

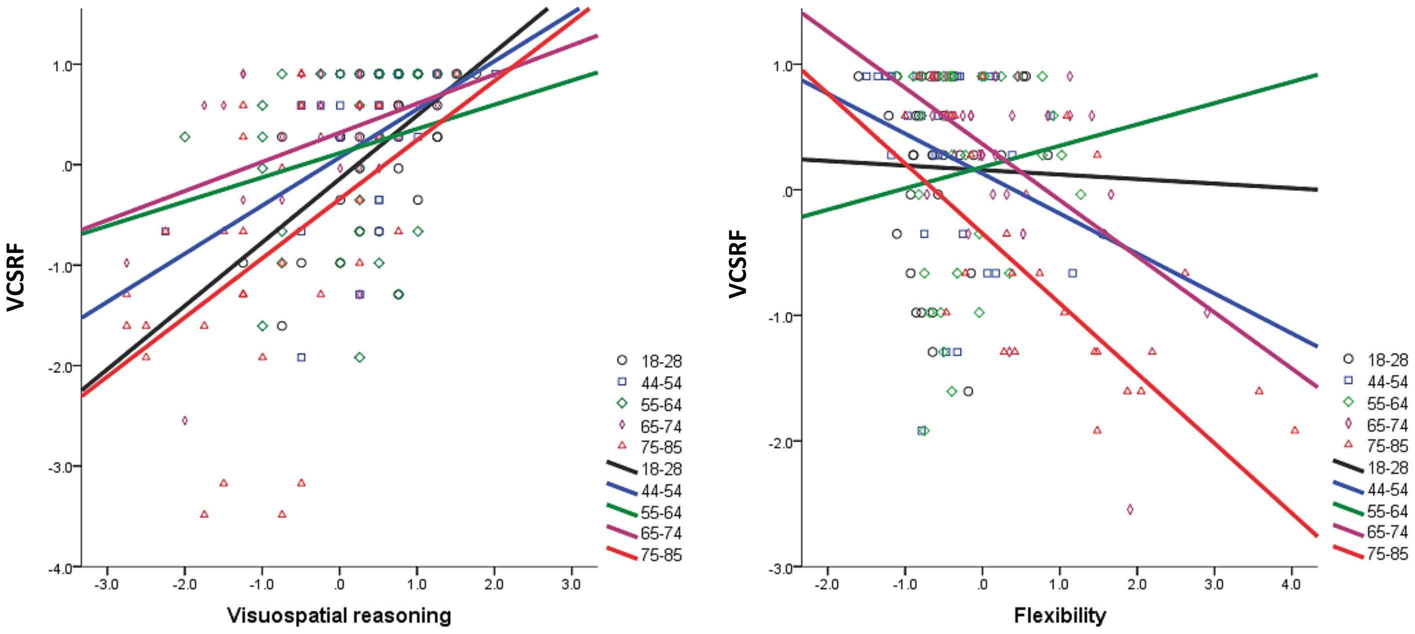


Figure 22. Correlations between comprehension in spatial reference frames (VCSRF: Env-C) and visuospatial reasoning (MR; left panel) and mental flexibility (TMT-B; right panel) across the adult life span.

5.4 Discussion

One of the main objectives of the present studies was to establish the validity of the novel tasks assessing spatial language abilities (i.e., Spatial Verbal Fluency task, SVF; Spatial Naming Test, SNT; Spatial Verbal Memory task, SVM; and Verbal Comprehension in Spatial Reference Frames task, VCSRF; also see Chapter 3) and to examine which demographic factors may influence spatial-verbal performance in order to develop appropriate normative data for the English population. The primary aim, however, was to reveal for the first time the adult-lifespan trajectories of different aspects of spatial language processing, including spatial-verbal fluency, naming, memory, and comprehension under different spatial reference frames, and contrast them to the trajectories of analogous non-spatial verbal abilities and non-verbal visuospatial abilities. A complementary goal was to investigate whether the relationships between the different aspects of spatial-verbal abilities with other cognitive processes change across the adult-lifespan or remain stable. The findings of these studies based on results with a large sample of healthy younger, middle-aged, and older adults between 18 to 85 years are discussed in turn below.

5.4.1 Novel spatial language tasks: Distribution of scores and validity assessment

5.4.1.1 Distribution of scores

Overall, in our general sample of healthy adults, the novel spatial language tests produced scores within acceptable limits for normally distributed data. Some of the tasks produced a negatively skewed distribution due to high floor and/or low ceiling effects. More specifically, scores for naming accuracy in the Spatial Naming Test presented a mild negative skewness, as the majority of participants produced accurate responses for at least the two thirds of the total number of the targeted spatial relations. The distribution of scores in naming tasks such as the Boston Naming Test (Kaplan et al., 2001) is typically negatively skewed (Hawkins & Bender, 2002), however, as most scores of cognitively intact individuals cluster closely to ceiling. Distributions of accuracy scores in all conditions of the VCSRF task were also negatively skewed, indicating that the left tail of the distributions was heavier and elongated compared to the right tail. This was mostly apparent in the self-centred and object-centred conditions where the majority of participants performed near or at ceiling levels. On the other hand, mild positive skewness was noted on the score distributions of the Spatial Verbal Fluency task as well as for the Spatial Verbal Memory task, including both the route and survey conditions. This pattern of score distributions is common both in verbal fluency and episodic memory tasks (Strauss et al., 2006). From a practical viewpoint, the skewed distribution means that the novel spatial language tests are not very sensitive at the upper score range. Thus, individual variations above a score of 75% or so are not very meaningful diagnostically. However, as the scores become progressively lower, their diagnostic significance increases.

5.4.1.2 Validity

After establishing the test-retest reliability of the novel spatial language tasks (see Section 3.4), we examined each test's concurrent and construct validity by a series of hypothesis-driven correlational analyses and an exploratory factor analysis using data from the entire sample of healthy adults aged between 18 and 85 years.

Spatial Verbal Fluency. The correlations between Spatial Verbal Fluency and both semantic (*animals, actions*) and phonemic (words beginning from *F*, *A*, and *S*) verbal fluency tasks were moderately high, confirming its nature as a task assessing fluent productivity in the verbal domain under restricted search conditions. Moreover, our factor-analytic findings revealed that all verbal fluency tasks loaded on the same factor. These findings are in accordance with previous studies reporting that category fluency scores correlate moderately / moderately-highly with phonemic fluency scores (e.g., Kosmidis et al., 2004; Tombaugh et al., 1999), while when using factor-analytic approaches these two types of fluency tasks load on one factor (e.g., Riva et al., 1999). We also found modest but significant correlations between each verbal fluency score, including spatial-verbal fluency performance, and performance on putative executive measures, including flexibility (TMT-B), inhibition (ST-CN), and working memory (DS-B and SS-B). These results offer further evidence for the convergent validity of the SVF task along with the other verbal fluency tasks as executive function measures, since effective verbal fluency depends on executive and attentional control processes as it requires effortful retrieval under restricted search conditions (Alvarez & Emory, 2006).

Spatial Naming Test. Naming accuracy for static and dynamic spatial relations (SNT) was significantly correlated with naming accuracy for objects (BNT) and actions (ANT). Moreover, there were strong correlations between spatial naming accuracy and performance on visuospatial tasks, including visuospatial reasoning (MR) and visual organization (HVOT), while performance on BNT and ANT, but not on SNT, was modestly related to verbal intelligence (MHVT). Previous studies have shown that BNT performance is moderately related to measures of verbal intelligence (Hawkins & Bender, 2002). Our factor-analytic results indicated that all naming tasks (i.e., SNT, BNT, and ANT) loaded on one single factor, confirming the validity of the novel SNT as a naming measure. Meanwhile, spatial naming accuracy also had a strong loading on one factor clustering visuospatial measures (including MR, MRT, HVOT, OPT, and visuospatial memory tasks). Both our correlational and factor-analytic findings provide evidence for the convergent and divergent construct validity of the SNT as a measure assessing naming abilities specifically for spatial relations.

Spatial-Verbal Memory. In order to assess the concurrent validity, the scores of the delayed trials of the route and survey conditions of the SVM task were compared to delayed recall scores of verbal (LM) and visuospatial (ROCF) episodic memory tasks, as well as to tasks of verbal and visuospatial short-term and working memory (DS, SS, and MPT). Both route and survey SVM recalls were highly correlated with episodic verbal memory (LM) and episodic visuospatial memory (ROCF) recall, as well as with visual (MPT) and visuospatial short-term (SS-F) and working (SS-B) memory capacity, and with performance on measures of various visuospatial abilities, including object-perspective taking (OPT), mental rotation (MRT), visual organization (HVOT), and visuospatial reasoning (MR). On the other hand, episodic verbal memory (LM) was not related to performance in any of the visuospatial memory tasks (ROCF, SS, MPT) or to performance on tasks of visuospatial abilities (OPT, MRT, HVOT, and MR). Moreover, according to factor analysis, spatial-verbal memory trials loaded on a factor along with verbal episodic memory, while SVM but not verbal memory was also related to the factor that clustered visuospatial abilities. These findings confirm that the SVM task is a valid measure of episodic memory for spatial descriptions.

VCSRF. The close connection between VCSRF performance and visuospatial abilities was established with the positive correlations revealed between accuracy of performance on the third-person-centred, object-centred, and particularly on the environment-centred condition with performance on object-perspective taking (OPT), mental rotation (MR), visual organization (HVOT), and visuospatial reasoning (MR) tasks. All participants performed at ceiling levels on the relative self-centred condition, and therefore, data from this condition did not correlate to any other measure. Results from the factorial analysis showed that the accuracy of performance on the absolute condition of the VCSRF task loaded solely onto the visuospatial factor. These findings confirm the nature of the VCSRF task as a visuospatial measure.

Summary. The convergent and divergent relations revealed from the correlational analyses and the exploratory factor analysis provide evidence of the validity of our novel tasks as measures of different aspects of spatial-verbal processing. Each spatial language measure loaded on distinguishable factors (i.e., fluency, naming, and episodic memory, respectively) along with their analogous (non-spatial) verbal measures. Meanwhile, the spatial language measures, but not the analogous (non-spatial) verbal measures, also loaded on a factor tapping visuospatial abilities.

5.4.2 Individual differences and adult-lifespan trajectories

After establishing the validity of our novel spatial-verbal tasks, we examined whether individual differences in age, education, and gender, may influence performance on each spatial language measure separately. We grouped our sample into two groups by educational level (compulsory and higher education level) and into five age groups in 10-year brackets (18-28, 45-54, 55-64, 65-74, and 75-85), and subsequently developed normative data for the English population across all measures, stratified by those demographic characteristics that contributed significantly to performance on each spatial-verbal task. These norms can be used when standard instructions and scoring procedures are followed.

Next, we identified the adult-lifespan trajectories of various aspects of cognitive functioning, including spatial language abilities as well as core and higher-order cognitive operations across the verbal and visuospatial domain. We sought to examine whether the patterns of potential age-related changes across the spatial-verbal abilities are similar or substantially different from equivalent non-spatial language abilities versus various visuospatial abilities, and investigated whether certain relationships between performance on spatial-verbal tasks and performance on other cognitive tasks remain stable or change across the adult lifespan. The results of these studies are discussed in turn below.

5.4.2.1 Processing resources and executive functions

One of the questions examined in the present studies is how typical ageing affects fundamental cognitive processes in the verbal and visuospatial domain, including processing speed and short-term and working memory capacity for verbal and visuospatial information, as well as inhibitory control and mental flexibility.

Our results revealed divergent patterns of ageing effects on processing resources, depending on the domain examined. Overall, we found that increasing age was associated with slower speed of information processing, in accordance with previous reports of age-related impairments in processing speed (Deary, Johnson, & Starr, 2010; Salthouse, 2000). However, age explained a larger proportion of the variance in processing speed for visual information (20%) than for verbal information (9%). Processing speed of visual information decreased as early as from the mid-50s whereas the speed of processing verbal information decreased approximately 20 years later, from the mid-70s. This prominent differential onset and rate of decreased processing speed emerging from our data is line with previous reports supporting that age-related slowing in processing information is more pronounced on visuospatial tasks than verbal tasks (Jenkins et al., 2000; Lawrence, Myerson, & Hale, 1998).

Even greater domain-specific discrepancies were observed in short-term and working memory capacity. On the one hand, short-term memory capacity for verbal information (i.e., strings of digits) peaked at mid-40s and then mildly dropped in the mid-50s to levels similar to those observed in individuals aged between 18-28 and remained unchanged thereafter throughout the lifespan, while the lifespan change in verbal working memory capacity was particularly subtle. On the other hand, short-term memory capacity for visual information (i.e., visual patterns) declined sharply from the mid-40s and continued to gradually decline until late adulthood, while short-term and working memory capacity for visuospatial information (i.e., spatial locations) declined linearly across the adult lifespan. These results provide striking evidence of modular and asynchronous cognitive changes across the lifespan, with cognitive resources for processing verbal information remaining relatively resilient to ageing effects whilst cognitive resources for processing visual and visuospatial information being particularly susceptible to ageing effects.

Past research has shown that age-related decrease in short-term and working memory capacity is greater for visuospatial compared to verbal material (Bopp & Verhaeghen, 2007; Dolman, Roy, Dimeck, & Hall, 2000; Hale et al., 2011; Jenkins et al., 2000; Leonards, Ibanez, & Giannakopoulos, 2002; Myerson, Emery, White, & Hale, 2003; Myerson, Hale, Rhee, & Jenkins, 1999), although there is also evidence against differential ageing trajectories for verbal and visuospatial working memory (Borella et al., 2008; Park et al., 2002). Procedural and sampling differences may be partially responsible for the inconsistent results of previous reports. Nevertheless, our results revealed clear differential ageing effects on memory for verbal (i.e., strings of digits), visual (i.e., visual patterns), and spatial (i.e., series of locations) material, highlighting the domain-specificity of the processing resources across the adult lifespan.

However, it should be noted that the tasks used in the present study (i.e., short-storage and reordering spans) emphasize rote maintenance without requiring high-demand processing operations of cognitive control. Past research on ageing effects on verbal working memory indicates that there are small age differences in tasks requiring passive storage and maintenance of information for a short period of time, whereas age differences are more pronounced in more demanding and complex tasks that require additional processing and manipulation of information (Bopp & Verhaeghen, 2007; Vecchi, Richardson, & Cavallini, 2005; for a meta-analysis see Bopp & Verhaeghen, 2005), like tasks that include distracters (Hartman, Dumas, & Nielson, 2001). Older adults seem to engage more neural resources and additional executive processes to accomplish simple computational goals that are typically completed with fewer resources by younger adults (Reuter-Lorenz & Cappell, 2008). In cases of simple verbal working memory tasks, older adults exhibit increased recruitment of prefrontal areas, which is postulated to reflect a functional compensation mechanism that allows older individuals to achieve equivalent memory performance with younger adults (Cappell, Gmeindl, & Reuter-Lorenz, 2010). Moreover, according to previous factor analytical and structural equation modelling results, verbal and visuospatial short-term memory are dissociable constructs, reflecting that the ability to maintain information for a limited period of time is domain-specific, whereas the ability to maintain either verbal or visuospatial information whilst performing demanding processing operations reflects a more domain-general factor for working memory capacity (Kane et al., 2004).

Another dimension of cognition examined in the present study is processing that requires increased putative executive operations, including mental flexibility (using the Trail Making test) and inhibitory control (using the Stroop task). Our results showed a steep impairment in inhibitory control from the mid-40s followed by gradual declines thereafter until late adulthood. These findings corroborate previous reports revealing the detrimental ageing effects on performance in various versions of the Stroop task (Bugg, DeLosh, Davalos, & Davis, 2009; Van Boxtel et al., 2001; Zalonis et al., 2009). A later onset of age-related decline was observed for set-shifting skills, with a mild impairment emerging from the mid-50s and a sharper decline from the mid-60s until late adulthood. Several studies have also reported that mental flexibility, as assessed by the TMT, declines with increasing age (e.g., Amodio et al., 2002; Hamdan & Hamdan, 2009; Oosterman et al., 2010; Wecker, Kramer, Hallam, & Delis, 2005; Zalonis et al., 2008), with a more accentuated decline from the from the mid-60s onwards (e.g., Perianez et al., 2007; Tombaugh, 2004).

Taken together, the results of the present study indicate that different components of processing resources (processing speed, rote maintenance, and executive control functions) start to change at different timepoints across the lifespan and at different rates, highlighting the importance of recognizing the diversity of processing resources in cognitive ageing. Moreover, our data seem to be incongruent with a common factor theory of ageing and with the existence of an indistinct verbal and visuospatial pool of resources in late adulthood (e.g., Salthouse, 1995). Instead, our results provide evidence for divergent domain-specific ageing trajectories for verbal and visuospatial processing capacities and echo that basic cognitive mechanisms in the nonverbal domain are disproportionately impaired by increasing age.

5.4.2.2 Visuospatial abilities and vocabulary knowledge

Another objective of the present studies was to produce fresh knowledge on age-related changes across the adult-lifespan in vocabulary knowledge and various visuospatial abilities, including visuospatial organization and reasoning, mental object-rotation, and object-perspective taking. Apart from age, we also examined potential gender differences in visuospatial abilities.

We found that vocabulary size significantly increased from the mid-40s and remained intact until late adulthood, confirming that semantic memory and conceptual knowledge is well preserved throughout the lifespan (Levine et al., 2002; Piolino, Desgranges, Benali, &

Eustache, 2002) or may even improve (e.g., Kennedy et al., 2015; see Verhaeghen, 2003, for a meta-analysis). Semantic knowledge is supported by a widely-distributed network with the anterior temporal lobes at its central hub (see Patterson, Nestor, & Rogers, 2007; Simmons & Martin, 2009; Visser, Jefferies, & Lambon Ralph, 2009, for reviews and meta-analyses), which seems to be more resilient to ageing effects than the medial temporal areas, which are critical for learning novel episodic information (Jack et al., 1997; Rugg & Vilberg, 2013).

On the other hand, our results showed age-related declines in all aspects of visuospatial processing, in accordance to existing literature addressing the impact of ageing on spatial cognition (for reviews, see Klencklen, Després, & Dufour, 2012; Lithfous, Dufour, & Després, 2013), though their magnitude appears to depend on the type of spatial subability examined. Consisted with previous reports, our data revealed a sharp decline in visuospatial organization during late adulthood (Giannakou & Kosmidis, 2006; Hoogendam et al., 2014; Hooper, 1983), while visuospatial reasoning started to decline from the mid-60s (Viskontas et al., 2004, 2005). These findings indicate that the specific demands of visuospatial tasks – to be able to rearrange fragmented pieces together into an integrated figure (HVOT) or to solve a novel problem that consists of abstract stimuli (MR) – have a different sensitivity to ageing processes.

A subtle decline in the ability to mentally rotate objects was apparent from the mid-50s onwards and became more pronounced from the mid-70s. This finding is in line with existing findings of age-related declines in mental imagery tasks, such as image generation, rotation, and maintenance (Kemps & Newson, 2007) and with previous cross-sectional studies reporting age-related impairments in mental object-rotation abilities (Band & Kok, 2000; Borella et al., 2014; Devlin & Wilson, 2010; Hertzog & Rypma, 1991; Inagaki et al., 2002; Jansen & Heil, 2009). Apart from age, our data yielded a significant effect of gender on mental object-rotation ability, with women performing poorer than men. Past research has also reported that males achieve significantly higher scores than females in tasks requiring mentally rotating objects (e.g., Hamilton, 1995), with sex differences being larger under stringent time limits (i.e., allowing 30 seconds or less per item) (for a meta-analysis, see Maeda & Yoon, 2012). Although several studies have reported average performance sex differences in mental rotation tasks favouring males, less attention has been paid on what extent the magnitude of the sex differences varies across age. We found that sex differences in favour of males were apparent across all age groups, in accordance with cross-sectional findings (Jansen & Heil, 2010) and findings focusing on older adults (Jansen & Kaltner, 2014). Mental rotation has been associated with increased right posterior parietal lobe activation, an area important for carrying out visuospatial transformations (Harris et al., 2000). Past research has revealed that during mental rotation males show predominantly parietal activation while females show inferior frontal activation, suggesting that the two genders may differ in processing visuospatial transformations based on mental rotation (Thomsen et al., 2000).

Another type of mental imagery, object-perspective taking examined with a spatial pointing task (OPT), started to significantly decline in a sharp linear way from the mid-50s until late adulthood. Previous studies have also reported a more accentuated impairment in performance during object-perspective taking pointing tasks than in mental object-rotation (e.g., Borella et al., 2014; Inagaki et al., 2002). These lifespan contrasts further support the dissociation between mental object-rotation and object-perspective-taking abilities, in accordance to psychometric findings with younger adults (Hegarty & Waller, 2004), and indicate that these two different types of spatial mental imagery are differentially sensitive to ageing processes. We also found significant sex differences in the object-perspective taking pointing task, favouring men, in accordance to existing literature (Meneghetti, Pazzaglia, & De Beni, 2012; Tarampi, Heydari, & Hegarty, 2016; Zacks et al., 2000; Zancada-Menendez et al., 2016). These gender-related differences were stable across the adult-lifespan.

In conclusion, the present findings further support that crystalized abilities, such as vocabulary knowledge, are well maintained across the adult lifespan whereas ageing has a negative impact on various visuospatial abilities, although the onset and the magnitude of the age-related decline depend on the visuospatial subability examined. Moreover, gender differences in visuospatial cognition seem to appear in tasks involving spatial mental imagery, as in mental object-rotation and object-perspective taking.

5.4.2.3 Verbal comprehension in spatial reference frames

Using the novel VCSRF task, the main objective of the present study was to investigate how individuals process descriptions of locative spatial relations under different spatial reference frames (SRF), including self-, third-person-, object-, and environment-centred frames, and to provide a comprehensive account of the effects of ageing and gender on this ability, from an adult-lifespan perspective.

Our results revealed a strong SRF effect, with individuals being substantially less accurate and slower in processing spatial descriptions within an environment-centred SRF, regardless their age. This finding is in accordance with the results from our pilot study with healthy young adults (Section 3.3.4.4) and is likely to reflect the additional and more demanding coordination operations required in representing how two objects are spatially related relatively to an external environmental point. Accuracy scores in all SRF ranged above chance levels across all age groups, indicating that the ability to form spatial representations within different coordinate systems from verbal descriptions is maintained throughout the adult-lifespan. Nevertheless, our results demonstrated that the impact of ageing on the ability to accurately process simple locative spatial descriptions varies depending on the SRF involved. Spatial-verbal processing from a self-centred perspective or within an object-centred SRF remained well preserved throughout the adult lifespan. By contrast, there was a mild but significant impairment in processing spatial descriptions from a third-person-perspective and a steep decline in processing spatial descriptions within an environment-centred SRF in late adulthood.

While the impact of ageing on processing spatial descriptions under diverse SRF has not been thoroughly investigated, recently, there has been an increasing interest in examining ageing effects on visuospatial perspective taking abilities using spatial pointing tasks. As previously explained, visuospatial perspective taking refers to the ability to imagine spatial relations from a perspective other than our egocentric perspective, requiring embodied simulations of self-based mental rotations (Kessler & Rutherford, 2010; Kessler &Thomson, 2010; Michelon & Zacks, 2006; Zacks & Michelon, 2005; Zacks et al., 2002). In line with our findings, previous studies using pointing tasks have shown an age-related impairment in spatial perspective taking performance using the Piaget's three-mountain task (Inagaki et al., 2002) or Kozhevnikov and Hegarty's (2001) object-perspective-taking test (OPT) (Borella et al., 2014; Zancada-Menendez et al., 2016). Moreover, there have been several reports of impaired allocentric processing in large-scale environments (e.g., Harris et al., 2012; Rodgers et al., 2012; Wiener et al., 2012, 2013) and generalized deficits in acquainting allocentric knowledge (Antonova et al., 2008; Gazova et al., 2013; Iaria et al., 2009; Newman & Kaszniak, 2000) in advanced age. Allocentric visuospatial processing based on external environmental points relies heavily on posterior hippocampal regions (Bird & Burgess, 2008; Doeller et al., 2008; Etchamendy & Bohbot, 2007; Konishi & Bohbot, 2013; Reuter-Lorenz & Park, 2010), so age-related allocentric processing deficits may arise from hippocampal alterations, as this structure is particularly vulnerable to ageing processes (Antonova et al., 2009; Apostolova et al., 2012; Moffat et al., 2006). In a recent study, Ruggiero and colleagues (2016) investigated the developmental course of spatial reference frames from childhood to late adulthood (from 6 to 89 years of age) using a memory task that involved judging descriptions of object locations from a self-centred or an object-centred perspective. In line with our findings, they found that, overall, egocentric judgments were more accurate and faster than allocentric judgements throughout the lifespan, consistent with the notion that allocentric spatial processing is fundamentally more demanding than egocentric processing (Klatzky, 1998). Moreover, they found a mirror-like developmental trajectory of performance with the youngest children and oldest adults performing slower and less accurately than all other age groups (Ruggiero et al., 2016). This finding is consistent with the view positing that the developmental trajectory of brain maturation and acquisition of visuospatial abilities in children is analogous to the trajectory of deterioration in brain and in complex visuospatial processing in the elderly.

The absence of an ageing effect on performance in the object-centred SRF was unexpected, but we believe that this was due to a ceiling effect. All age groups exhibited approximately 95% accuracy in their responses within this frame, and therefore the simplicity of the task may have masked potential declines. All experimental conditions of the VCSRF task were considered within the medium-sized peripersonal/vista space (see Montello, 1993), but in contrast to the other two non-self-centred conditions (i.e., the third-person- and environment-centred SRF), the reference object in the object-centred SRF also defined the coordinate axial system used to describe the location of the located object. Therefore, the spatial mental transformation operations involved in this frame are likely quantitatively and qualitatively different from those involved in third-person perspective taking or within frames defined by external environmental points. Consistent with this assumption is the fact that participants required about the same time to complete the self-centred and the object-centred conditions of the task.

Another factor that may have contributed to the invariant performance of participants in the object-centred SRF is the reference object used, i.e., a car model. Cars are particularly familiar objects that encompass rich situation knowledge. Therefore, apart from the geometric properties of the reference object used (i.e., the car model), it is likely that prior situational knowledge regarding cars was also represented during the linguistic processing of the spatial relations in the object-centred SRF, as the functional geometric framework theory would predict (Coventry & Garrod, 2004, 2005; see Section 2.1). It is also likely that the prior functional and situational knowledge regarding cars triggered robust embodied simulations of self-based mental rotations (Kessler & Rutherford, 2010; Kessler & Thomson, 2010; Michelon & Zacks, 2006) that facilitated performance. It is worth mentioning that participants of different ages reported that they mentally placed themselves in the driver's seat of the car while performing the task, which supports our assumptions. Future studies examining linguistic processing of spatial relations from an object-centred perspective should consider the inclusion of different reference objects pertaining varied levels of prior situation knowledge to examine the role of object knowledge in object-centred processing of spatial descriptions. Another factor that should be considered in future investigations is the magnitude of the angular difference between the object's perspective and the participant's self-centred perspective. In the present study, the angle between the object's perspective and the participant's perspective was fixed at 90˚, however, previous research has revealed a significant association between angular disparity and performance in object-perspective-taking pointing tasks, with decreased speed and accuracy as the angular disparity increased (Kessler & Thomson, 2010; Zacks & Michelon, 2005), especially for items requiring a perspective change of more than 90˚ (Kozhevnikov & Hegarty, 2001).

The different impact of ageing on processing spatial descriptions under different perspectives confirms existing classification models of space based on distinct coordinate systems that may serve as reference frames during visuospatial operations (Burgess, 2006; Carlson, 1999; Levinson, 1996, 2003). Moreover, it confirms that processing under different spatial frames of reference is supported, at least partially, by different neural hubs (Committeri et al., 2004) that are differentially vulnerable to normal ageing processes. Finally, establishing the trajectories of decline in the accuracy and speed of processing spatial descriptions under different frames of reference in typical ageing can be useful for clinical purposes. Future studies examining whether these processes are differentially affected in atypical ageing could help identify signs of distinct neurodegenerative conditions, such as Alzheimer's disease.

Another topic examined in the present study concerned the potential overlaps and discrepancies among the trajectories of spatial-verbal processing within an environment-centred SRF and various non-verbal visuospatial abilities, including object-based mental rotation (MRT), object-perspective-taking (OPT), visual organization (HVOT), and visuospatial reasoning (MR). The absolute SRF was selected over the other frames based on the observed condition effects pointing to greater variability of performance within this SRF. As discussed earlier, age-related impairments were found in all abilities examined, though their onset and magnitude appeared to depend on the type of visuospatial subability examined. A considerable overlap in terms of decline onset was observed across spatial-verbal processing within an environment-centred SRF, visual organization, and object-based mental rotation, with a significant decline observed in late adulthood. Visuospatial reasoning involving complex relational integration processing started to deteriorate more gradually, with a significant decline emerging from the mid-60s, while object-perspective-taking declined substantially as early as from the mid-50s. Nevertheless, these onset discrepancies might partially reflect differences in the level of task difficulty, as the OPT is rather difficult to complete (resulting in floor effects) and the MR includes items of progressively increasing difficulty. Taken together, these findings suggest that as people age, they can cope relatively well with visuospatial demands of medium level of difficulty up until the early mid-70s, but exhibit clear impairments beyond that age. In late adulthood, however, the magnitude of the decline in environment-centred spatial-verbal processing was comparable to that of object-perspective-taking, and more accentuated compared to those of the rest visuospatial abilities examined, indicating that demanding self-based mental rotation abilities are particularly susceptible during later life. This is of great importance if we consider how necessary it is in daily experience to be able to shift from an egocentric viewpoint and mentally reorganize visuospatial representations according to a different, external-to-the-self, reference frame.

A supplementary objective was to explore the mechanisms underlying the ageing effects on processing locative spatial descriptions under different spatial reference frames. To this end, we examined potential adult-lifespan changes in the relationships between environment-centred spatial-verbal processing and visuospatial reasoning and mental flexibility, respectively. Results yielded a stable positive correlation between environment-centred spatial-verbal processing and visuospatial reasoning, which may suggest that as our non-verbal perceptual problem-solving skills decline with increasing age, so does our ability to mentally reorganize spatial relations with respect to a non-self-centred frame of reference. Furthermore, mental flexibility was not related to environment-centred processing abilities across younger and middle-aged adults, but a significant negative association between these two types of cognition emerged in older adults. These findings suggest that poor mental flexibility skills may mediate the ageing effects on perspective taking skills, reflecting a perseveration-like difficulty to disengage from an egocentric viewpoint of the world. There exists correlational evidence suggesting that different kinds of perspective taking abilities, such as social/affective and visuospatial, are related (e.g., Kessler & Wang, 2012; Erle & Topolinski, 2017). Apart from documented impairments in spatial perspective taking, older adults exhibit deficits in their ability to represent other’s mental states (for an excellent review on theory of mind studies in ageing, see Moran, 2014), reflecting an age-related decline in general fluid meta-representational abilities.

Regarding sex differences, males were more accurate than females in processing spatial descriptions that were framed with respect to a fixed external point in the environment (absolute SRF). This finding is in accordance with several recent studies demonstrating a male advantage in pointing tasks requiring visuospatial object-perspective-taking (e.g., Meneghetti, Pazzaglia, & De Beni, 2012; Tarampi, Heydari, & Hegarty, 2016; Zacks et al., 2002; Zancada-Menendez et al., 2016). Another aim was to assess sex differences in VCSRF performance at different ages. We found no significant age by gender interaction effects on spatial-verbal processing within an absolute SRF, indicating comparable sex differences across the adult lifespan. This is consistent with previous studies reporting that, despite the general age-related decline in spatial abilities (Driscoll et al., 2005) and in spatial perspective taking abilities (Borella et al., 2014; Zancada-Menendez et al., 2016), sex differences favouring men do not diminish with age. Meanwhile, no sex differences were observed in spatial-verbal processing from a third-person perspective. This is particularly interesting since the ability to represent spatial relations from any perspective other than a first-person-viewpoint, including a third-person-centred perspective (Kessler & Wang, 2012) requires self-based mental rotation abilities (Kessler & Rutherford, 2010; Michelon & Zacks, 2006; Zacks et al., 2002). However, framing spatial perspective-taking tasks as social, by modifying them to include human figures, may diminish sex discrepancies (Tarampi, Heydari, & Hegarty, 2016; Wraga et al., 2006). Past research has also shown that sex differences in spatial tasks requiring third-person perspective taking may arise from differences in the strategies employed to perform the task, with males showing object-based strategies and females employing egocentric perspective transformations (Kaiser et al., 2008).

In summary, the present research showed that self-centred processing of spatial descriptions was the most accurate and fast whilst environment-centred was the least accurate and fast compared to all spatial reference frames considered. Ageing had differential effects on spatial-verbal processing, depending on the spatial reference frame considered: self- and object-centred processing remained unchanged throughout the lifespan whereas processing from a third-person- and especially from an environment-centred frame declined in late adulthood. This suggests that processing under different spatial frames of reference is supported, at least partially, by different cognitive operations and neural hubs, that are differently sensitive to typical ageing. From a theoretical standpoint, these findings support previous classification models of spatial reference frames (Carlson, 1999; Levinson, 1996, 2003) and add to previous neuropsychological work (e.g., Committeri et al., 2004) suggesting that spatial reference frames constitute specialized functions. We also found that changes in visuospatial abilities and mental flexibility may mediate the ageing effects on verbal processing under different spatial reference frames. Finally, sex differences in processing locative spatial descriptions varied depending on the spatial reference frame considered: males performed better than females within an environment-centred frame, but when the reference frame was defined by a social agent these sex differences disappeared.

5.4.2.4 Episodic memory

Using the new SVM task, the present research aimed to investigate short- and long-term episodic memory capacity for spatial descriptions presented from different perspectives, including a person-centred route description and a landmark-centred survey description, contrasted against episodic memory for non-spatial verbal information (LM) and non-verbal visuospatial information (ROCF), from an adult-lifespan perspective.

Our results showed poorer immediate and long-term memory capacity for survey descriptions compared to route descriptions and non-spatial verbal information, as well as poorer capacity for route descriptions compared to non-spatial verbal information, for participants of all ages. These findings imply that people may engage, at least partially, distinct cognitive resources and strategies during verbal encoding of different types of information. Spatial descriptions can be processed either verbally, focussing on the propositional information of the description, or using imagery strategies, which entail transforming the spatial description into a spatial image (MacLeod, Hunt, & Mathews, 1978). Results from studies with healthy young adults performing sentence-picture and sentence-sentence verification tasks for spatial relations have revealed that people can use a dual-representational model to process simple spatial sentences, since they can effectively generate both verbal and pictorial representations when required (Noordzij, Van der Lubbe, & Postma, 2005). However, people tend to adopt a pictorial over a verbal strategy under high cognitive loads (Noordzij & Postma, 2005). In fact, evidence suggests that the use of imagery strategies is beneficial to processing route descriptions (e.g., Gyselinck, De Beni, Pazzaglia, Meneghetti, & Mondoloni, 2007) and is more effective than the use of verbal strategies in constructing and maintaining a spatial mental model from route descriptions (Gyselinck, Meneghetti, De Bedni, & Pazzaglia, 2009). In line with this notion, a series of experiments involving demanding interference tasks by Bergen, Lindsay, Matlock, and Narayanan (2007) showed that processing spatial sentences describing motion scenes involves automatic activation of internal mental simulations of the described scenes. Moreover, research with blind individuals indicates that spatial mental models can be effectively generated from verbal descriptions in the absence of visual experience, but less efficiently when the descriptions are presented from a survey compared to a route perspective (Noordzij, Zuidhoek, & Postma, 2006), suggesting that processing survey descriptions might require additional integration operations that draw from visuoperceptual abilities to a greater extent than the operations involved in processing route descriptions.

Regarding adult-lifespan trajectories, results showed that ageing had a similar effect on immediate memory recall, regardless the type of information considered, with significant declines from the mid-60s. However, we found significant discrepancies in the adult-lifespan trajectories of long-term episodic memory capacity, depending on the type of information considered. More specifically, memory for spatial descriptions presented either from a route or a survey perspective remained relatively stable until early midlife and began to significantly decline from the mid-60s. Similarly, memory for (non-verbal) visuospatial information was substantially deteriorated in late adulthood. By contrast, the changes in (non-spatial) verbal episodic memory capacity were particularly mild across the adult-lifespan. Some previous studies have failed to provide evidence of a differential decline in episodic memory for verbal versus visuospatial information (Kemps & Newson, 2006; Park et al., 2002; Salthouse, 1995), supporting a generalised age-related deterioration of episodic memory abilities. Nevertheless, our results are in accordance with several investigations reporting that verbal recollection is more resilient to age-related deterioration than nonverbal recollection (Jenkins et al., 2000; Murre, Janseen, Rouw, & Metter, 2013; Tubi & Calev, 1989). In fact, according to the results of a recent study with data obtained from over 28000 participants aged between 11 and 80, aspects of visuospatial memory start to decline as early as from 18 years of age at a rate twice as fast as the decrease in verbal memory (Murre et al., 2013).

Our novel findings revealing differential ageing effects on verbal versus spatial and spatial-verbal memory could suggest that older adults may have difficulties in effectively developing and maintaining complex spatial mental representations, especially from spatial descriptions. According to several studies, older adults exhibit a preserved ability to construct and use spatial mental models from texts (e.g., Radvansky, Copeland, & Zwaan, 2003; Radvansky, Copeland, Berish, & Dijkstra, 2003), however, they show impairments when they have to integrate and maintain multiple spatial information (e.g., Copeland & Radvansky, 2007). Moreover, there is evidence suggesting that older adults may further exhibit a specific difficulty in managing and translating verbal information into a complex spatial mental model. Research investigating age-related differences in spatial learning and memory based on visual or verbal encoding (i.e., through exposure to visual displays of object arrays or maps or spatial sentences, respectively) has shown that older and younger adults perform similarly in identifying spatial relations between objects (Copeland & Radvansky, 2007) and recalling a route in map-drawing tasks (Meneghetti, Borella, Grasso, & De Beni, 2011; Meneghetti, Borella, Gyselinck, & De Beni, 2012) when spatial information are encoded visually, but when spatial information are encoded verbally, older adults perform poorer than younger adults.

The observed age-related declines in the ability to maintain spatial descriptions from either route or survey perspectives could also reflect differences in selecting and using imagery strategies, which, as past research has shown (Gyselinck et al., 2007, 2009), can facilitate the construction of spatial mental representations of described environments. In fact, at the end of the SVM task, when our participants were exploratorily asked how they managed to maintain the information from the spatial descriptions, younger and middle-aged individuals reported that they tried to mentally construct a visual representation of the information described (i.e., the route or the town layout, respectively), whereas older adults reported that they tried to maintain the propositional information of the descriptions. The adult-lifespan changes in the correlations between episodic memory capacity for different types of information are in line with these assumptions: overall, higher capacity to maintain verbal information in the long-term was associated with higher capacity to maintain spatial descriptions throughout the lifespan. By contrast, higher long-term memory capacity for visuospatial information was positively related to memory capacity for both route- and survey-based spatial descriptions among younger and middle-aged adults, but not in older adults. These findings indicate that older adults rely on different cognitive resources and recruit different coping strategies to remember spatial information after verbal encoding.

The strategies people use to remember new information have a substantial influence on memory performance. Identifying what kinds of strategies people select and use is therefore particularly important in understanding individual differences in learning and memory. Building on the present findings and observations, future work should examine more systematically potential age-related differences in the selection and use of language- and imagery-based strategies to remember spatial information through verbal encoding. Spontaneous selection and use of such strategies, including mentally rehearsing the propositional information of the descriptions or mentally constructing a visual representation of the information described, could be examined by self-reports made either concurrently or retrospectively of testing. This design can also provide significant insights on potential discrepancies in the strategies employed for recalling route- and survey-based descriptions, and whether certain strategies (i.e., imagery-based) are more effective in maintaining spatial descriptions from different perspectives. If indeed older adults exhibit poorer spatial-verbal memory performance because they are less likely to recruit effective strategies than younger adults, then it would be particularly interesting to examine whether prior knowledge of such strategies may diminish to some extent the observed age-related differences in spatial-verbal memory. This could be achieved by providing older adults explicit information and instructions on using effective strategies prior to testing.

It is highly likely that this shift from recruiting both verbal and pictorial strategies among younger and middle-aged adults to predominantly recruiting verbal strategies in advanced age emerges as a result of the age-related deterioration of visuospatial cognition and mental imagery abilities. In our sample, verbal abilities were far more resilient to ageing effects compared to visuospatial abilities, including imagery operations of mental object-rotation and object-perspective taking. A complementary mechanism underlying these discrepancies could be linked to the changes in core cognitive operations that occur in typical ageing. In other words, the observed declines in processing speed and the decrements in aspects of short-term and working memory capacity may mediate the ageing effects on processing and maintaining spatial descriptions from different perspectives. Individual differences have often been used to explain sources of variance in memory function. For example, it has been proposed that working memory capacity mediates age effects in episodic learning (Kirasic, Allen, Dobson, & Binder, 1996) while Park et al. (2002) found that individual differences in speed and working memory accounted for a large proportion of the age-related variance on free recall of verbal and spatial material. Past research involving dual task paradigms has revealed that both verbal and visuospatial components of working memory are involved in the memory of descriptions that contain spatial information (Brunyé & Taylor, 2007; De Beni, Pazzaglia, Gyselinck, & Meneghetti, 2005). However, visuospatial abilities, including visuospatial working memory capacity and mental object-rotation abilities, seem to have a more profound role in the ability to maintain and recall spatial descriptions, at least from a route perspective (Meneghetti, De Beni, Gyselinck, & Pazzaglia, 2013; Meneghetti, Gyselinck, Pazzaglia, & De Beni, 2009), and especially in cognitively demanding paradigms (Meneghetti et al., 2013).

To conclude, the present study provides fresh insight into episodic memory representations for different types of information, including (non-spatial) verbal, (non-verbal) visuospatial, and spatial-verbal material, from an adult-lifespan perspective. Our results showed impaired long-term memory capacity for spatial descriptions, presented either from a (person-centred) route or an (extrinsic) survey perspective, and for (non-verbal) visuospatial information, but relatively intact long-term memory capacity for verbal information. Therefore, our research confirms a modular, rather than a generalised model of age-associated decline in long-term episodic memory with ageing. Moreover, the synchronous age-related impairment of spatial-verbal and (non-verbal) visuospatial long-term memory indicates that spatial language and visuospatial representations in memory are supported, at least in part, by common neural networks in the brain that are comparably affected by typical ageing processes.

5.4.2.5 Naming

In this study, we examined lexical retrieval abilities using picture-naming tasks and identified the adult-lifespan trajectories of naming static and dynamic locative spatial relations between objects (SNT) and directly contrasted them against the adult-lifespan trajectories of object (BNT) and action (ANT) naming skills, as well as visuospatial abilities.

Using the SNT, our results showed significant age-related declines in spatial naming accuracy and speed. More specifically, the ability to accurately describe and name static spatial relations between two concrete objects remained stable until the mid-60s and declined sharply in the mid-70s, while the ability to accurately describe dynamic spatial relations between objects (i.e., transitional changes of location) started to mildly drop as early as from the mid-50s and begun to significantly decline from the mid-60s. Moreover, there was a steady linear decrease on the speed of naming static and dynamic spatial relations with increasing age. Meanwhile, our results demonstrated contrasting patterns of naming performance across the adult lifespan depending on the naming condition. Whilst spatial naming accuracy declined with increasing age, object naming accuracy slightly improved in midlife and remained intact until late adulthood, while age-related changes in accurately naming actions were too subtle and did not reach statistically significant levels. On the other hand, age-related declines in several visuospatial abilities were apparent from the mid-60s with a more pronounced impairment in late adulthood (see Section 5.4.2.2).

This divergence may appear surprising at first given the close relation amongst BNT, ANT, and SNT performances, as revealed from the factor analytical and correlational results (Sections 5.3.2 and 5.4.1). Picture confrontation naming tasks have long been recognized as one of the most useful means to assess language abilities and are considered particularly sensitive in identifying neurogenic language deficits (Welch, Doineau, Johnson, & Kind, 1996). Nevertheless, apart from semantic processing and lexical retrieval abilities (Ralph, McClelland, Patterson, Galton, & Hodges, 2001), naming performance also depends to some extent on certain fundamental perceptual processes, including the visual perception of the target item. As previously discussed (see Section 2.1), the linguistic representation and encoding of spatial relations is largely determined by perceptually-grounded representations of the gross geometric relations between the located and reference objects (Hayward & Tarr, 1995; Landau & Jackendoff, 1993), especially if the objects are not primarily characterized by a situation-specific functional relationship (Coventry & Garrod, 2004, 2005; Landau, 2016). It is highly likely that the increased vulnerability of spatial naming accuracy with advanced age, which is comparable to the age-related declines in visuospatial abilities and in direct contrast to the ageing-resilient object and action naming abilities, can be accounted for by the greater perceptual demands of visually representing *relations* between entities rather than merely recognising a single entity per se. By extent, it can be argued that naming dynamic spatial relations requires even more complex perceptual representations, as it entails monitoring the transitional changes of location of the figure object relatively to the ground object, which would explain our finding of a greater age-related decline in describing dynamic spatial relations compared to static. In fact, past research has shown that older adults may be less sensitive to global motion processing (Conlon & Herkes, 2008), motion perception (Snowden & Kavanagh, 2006), and direction identification (Bennet, Sekuler, & Sekuler, 2007) compared to younger individuals.

Taken together, these results along with the finding of a significant age-related increase of vocabulary knowledge, indicate that spatial naming involves more demanding perceptual and visuospatial processing, whilst object and action naming performance is likely to be more closely related to crystallized semantic knowledge which typically remains stable or even improves with increasing age (Craik & Bialystok, 2006; Kennedy et al., 2015; Verhaeghen, 2003). In fact, object naming deficits in patients with progressive anterior temporal atrophy leading to semantic dementia can be accounted for by semantic impairment alone (Ralph et al., 2001). This assumption is supported by our factor analytical and correlational results (Sections 5.3.2 and 5.4.1), which showed that spatial naming is equally related to other non-spatial naming tasks and with tasks tapping non-linguistic visuospatial abilities, while there were no significant associations between non-spatial naming and non-linguistic visuospatial performance. This hypothesis is also in line with behavioural (e.g., Coventry et al., 2014; Hayward & Tarr, 1995), developmental (Balcomb et al., 2011), cross-linguistic (e.g., Munnich et al., 2001), and neuroimaging (e.g., Wallentin et al., 2005; Noordzij et al., 2008) studies revealing a strong connection between linguistic and non-linguistic representations of space. The strong relation between spatial naming and visuospatial reasoning did not change substantially across the lifespan, however, increased vocabulary size was associated with more accurate descriptions of spatial relations among individuals aged between 75 and 85. This suggests that older adults, who presented the greatest decline in visuospatial abilities, may recruit additional symbolic representations and semantic knowledge that is available to them as a compensatory strategy while coping with the demands of a spatial naming task.

Consistent with our findings, several studies with neurologically unimpaired individuals suggest that lexical retrieval for objects as measured by picture-confrontation naming tasks is generally well preserved in ageing (e.g., Béland & Lecours, 1990; Schmitter-Edgecombe et al., 2000; Welch et al., 1996; Wierenga et al., 2008), although some reports have noted subtle naming declines for objects and/or actions after the age of 70 (Barresi et al., 2000; Mortensen et al., 2008; Zec et al., 2005). Nevertheless, speed of naming performance for both object and action pictures was significantly slower from the mid-60s and further decreased in late adulthood. It has been argued that slowed processing speed may modulate age-related difficulties in lexical retrieval (Facal et al., 2012), however, differences between younger and older adults usually appertain to naming speed and not to naming accuracy (for a review, see Goulet et al., 1994).

In our study, participants of all age groups performed more accurately and faster in naming actions compared to objects, in line with previous investigations reporting that action naming in healthy ageing is better preserved than object naming (Nicholas et al., 1985, 1997; Barresi et al., 2000). One possible explanation of this finding could be that the lexical retrieval of verbs is easier than the retrieval of nouns, since verbs consist the most important word class in language. However, it has been argued that there might be an implied sentence context for verbs that may provide cues and facilitate retrieval (Nicholas et al., 1985). Nevertheless, our results yielded parallel trajectories of naming accuracy for concrete objects (nouns) and concrete actions (verbs), with maximum performance reached by middle-aged adults and minor, non-significant declines in older individuals.

It remains unclear whether grammatical class or semantic properties, or both, underlie lexical organization, processing, and retrieval. On the one hand, lesion studies have suggested a double dissociation between noun and verb retrieval in picture naming tasks (Sörös et al., 2003), with damage in the left anterior and middle temporal lobe resulting in impaired noun production, while damage in left frontal regions, including the premotor cortex, resulting in impaired verb production (Damasio & Tranel, 1993; Piras & Marangolo, 2007). However, other lesion studies have found that the disruption of fronto-temporal networks may result in deficits in lexical retrieval of both object and action names (Lu et al., 2002), and that semantic distinctions, such as hand imagery (manipulability), and not grammatical word-class differences (nouns vs verbs), more accurately account for the discrepancy in object and action naming performance among patient and control participants (e.g., Arevalo et al., 2007). In line with this, several neuroimaging studies with healthy individuals have yielded similar cortical activation patterns during comprehension (Vigliocco et al., 2006; Moseley & Pulvermüller, 2014) and naming (Liljeström et al., 2008; Sörös et al., 2003) tasks involving nouns (objects) and verbs (actions), indicating that semantic features, including sensorimotor dimensions (Vigliocco et al., 2006) such as manipulability (Saccuman et al., 2006), or concreteness/abstractness (Moseley & Pulvermüller, 2014), rather than grammatical class, define lexical organization in the brain.

The divergent lifespan trajectories of naming performance for objects, actions, and spatial relations revealed in our study, may reflect differential ageing effects on the brain. While patient studies and neuroimaging investigations have previously shown that word production for distinct classes (i.e., nouns and verbs) is underpinned by overlapping neural networks that include the left prefrontal and anterior temporal regions (Cotelli et al., 2012; Havas et al., 2015; Liljeström et al., 2008; Lu et al., 2002; Saccuman et al., 2006; Tyler et al., 2001), several neuroimaging (Amorapanth et al., 2010; Damasio et al., 2001) as well as lesion (Göksun et al., 2013; Kemmerer & Tranel, 2003; Tranel & Kemmerer, 2004; Wu et al., 2007) studies indicate that retrieval of spatial prepositions during confrontation picture naming tasks is additionally supported by parietal regions. Large morphometry studies have found that, along with frontal or prefrontal regions, parietal cortices, which are typically involved in visuospatial processing (Apostolova et al., 2012; Yamamoto & DeGirolamo, 2012), are particularly vulnerable to ageing effects (Abe et al., 2008; Fjell et al., 2009; Sowell et al., 2003), while inferior temporal regions, which are critical for semantic memory, seem to be less affected by age (Fjell et al., 2009).

Regarding sex differences, we found a significant contribution of gender on the accuracy of naming dynamic spatial relations, with male individuals achieving higher scores regardless of age and educational level. Although the question of whether there are sex differences in naming static and dynamic spatial relations has not been directly addressed in the past, our findings corroborate previous reports of a male advantage in dynamic spatial processing (Contreras, Colom, Shih, Alava, & Santacreu, 2001; Saccuzzo, Craig, Johnson, & Larson, 1996). While performance factors, such as response latencies, play a trivial role in the sex differences in dynamic spatial abilities (Contreras, Rubio, Pena, Colom, & Santacreu, 2007; Pena, Contreras, Shih, & Santacreu, 2008), differences in employing coping strategies during task completion can partially explain them (Pena et al., 2008). In line these findings, it has been shown that sex differences in spatial abilities may diminish with practice and sufficient training (e.g., Feng, Spence, & Pratt, 2007), which further supports that females do not underperform on spatial tasks because of actual lack of abilities.

To summarize, the primary goal of the present study was to gain insight into whether ageing affects our ability to effectively name locative static and dynamic spatial relations between two objects, for the first time. Moreover, we sought to examine the mapping between spatial naming and object and action naming as well as non-linguistic spatial abilities across the adult lifespan. Our results demonstrated divergent patterns of change in naming performance across the adult lifespan: there was a clear deterioration in naming spatial relations, with a more pronounced decline in dynamic spatial naming, whilst object and action naming remained well preserved across adulthood. The trajectories of spatial naming decline were comparable to the impairments in visuospatial abilities, indicating that age differences in confrontational spatial language production may be attributable to age-dependent neural changes in areas associated to visuospatial processing, confirming that the linguistic and perceptual representations of space are supported by similar neural networks (Chatterjee, 2001; Noordzij et al., 2008).

5.4.2.6 Verbal fluency

In the present studies, we examined verbal fluency based on different semantic (i.e., *locative spatial relations*, *animals*, *and actions*) and phonemic (i.e., words beginning from the letters *F*, *A*, and *S*) cues, from an individual-differences, adult-lifespan perspective. One of the goals was to identify and contrast the adult-lifespan trajectories of semantically- and phonemically-cued word production. We expected differential effects of ageing on the two types of verbal fluency, since semantic fluency relies heavily on semantic memory but requires effective search processes, while phonemic fluency requires effective initiation and shifting skills (Kosmidis et al., 2004). Moreover, we examined to what extent the age trajectories of diverse semantic word outputs overlap or whether they differ as a function of the word class involved. We therefore compared cued word production across three distinct semantic categories that are represented by grammatically distinct word classes, and more specifically *animals* (nouns), *actions* (verbs), and *locative spatial relations* (spatial prepositions).

Our results showed that word production on the spatial verbal fluency task is a function of both age and education. Lower level of education has been repeatedly identified as a risk factor for poorer verbal production in both semantic and phonemic fluency tasks (e.g., Cavaco et al., 2013; Kosmidis et al., 2004a; Kosmidis et al., 2004b; Mathuranath, George, Cherian, Alexander, & Sarma, 2003; Tombaugh et al., 1999; Van Der Elst, Van Boxtel, Van Breukelen, & Jolles, 2006; Woods et al., 2005). However, we found no sex differences on the produced number of words denoting spatial relations between objects. There have been some reports of sex differences in executive word production tasks, favouring women, but these discrepancies are apparent primarily in phonemic processing (e.g., Weiss et al., 2003; Weiss et al., 2006).

Overall, our findings provide new evidence indicating that word production according to diverse cues declines in advanced age, independently of the grammatical word class involved. More specifically, fluency performance across all semantic categories peaked in younger middle-aged adults (between 45-54) and decreased linearly thereafter until late adulthood. In line with our results, previous studies have reported that semantic word production is sensitive to the effects of ageing (e.g., Brickman et al., 2005; Harrison et al., 2000), with highest word outputs found amongst individuals in their 40s and significantly poorer production from the 60s (e.g., Cavaco et al., 2013; Rodriguez-Aranda & Martinussen, 2006; Tombaugh et al., 1999). By contrast, and in accordance to previous reports of minor (Tombaugh et al., 1999) or no (e.g., Bolla, Lindgren, Bonaccorsy, & Bleecker, 1990; Mathuranath et al., 2003) ageing effects on phonemic verbal fluency, including a British sample of healthy adults (Harrison et al., 2000), our results showed that phonemic processing in fluency tasks is less affected by increasing age. These findings further confirm that, overall, word generation based on semantic cues is more sensitive to the effects of ageing compared to phonemic verbal fluency (Brickman et al., 2005; Cavaco et al., 2013; Van Der Elst et al., 2006).

In our study, similar adult-lifespan trajectories were identified across verbal production of spatial prepositions (spatial-verbal fluency), nouns (animals), and verbs (action verbal fluency). This overlap of the lifespan trajectories suggests that semantically-cued language production in the absence of prompting stimuli (such as pictures) relies on common semantic search and retrieval processes, regardless the grammatical class involved. However, we found a moderately sharper decline in action compared to animal and spatial verbal fluency amongst typically developing older individuals. Previous studies have found lower action than lexical and animal word production amongst patients with subcortical dementia due to Parkinson’s disease (Piatt et al., 1999) or dementias predominantly affecting the frontal cortex such as behavioural variant frontotemporal dementia (Davis et al., 2010), suggesting that effective verb retrieval relies more heavily on frontal-subcortical circuits. On the other hand, noun retrieval is significantly impaired in conditions predominantly affecting temporoparietal regions, such as patients with Alzheimer's disease (Davis et al., 2010; Delbeuck, Debachy, Pasquier, & Moroni, 2013).

To our knowledge, this is the first time that the distinct word class of spatial prepositions was considered in a word production task along with semantic (nouns), action (verbs), and phonological (words beginning from *F*, *A*, or *S*) fluency tasks. Although we found that spatial-verbal fluency was affected comparably to semantic and action fluency by increasing age, it would be particularly interesting to examine whether fluency outputs in atypical ageing may be a function of the word class involved. Overall, in our sample of cognitively intact adults, spatial-verbal fluency was highly correlated with semantic, action, and phonological fluency, and moderately correlated with putative executive function measures (mental flexibility, inhibitory control, and working memory). Meanwhile, our factor-analytic results showed a trivial relation between spatial-verbal fluency and visuospatial abilities, which, in fact, did not change substantially across the lifespan. By contrast, richer vocabulary knowledge was associated with increased production of spatial prepositions in later life. Taken all together, these findings indicate that lexical retrieval for words denoting locations in verbal fluency tasks may be remotely connected to visuospatial abilities, and that it is rather comparable to lexical retrieval of other categories.

5.4.2.7 Conclusions

Although very few studies have examined spatial language skills from an ageing perspective, the associated changes in sensorimotor and cognitive functions make ageing a particularly interesting field to study this distinct aspect of cognition, which constitutes a natural bridge between the linguistic and the perceptual world. The present series of studies examined different aspects of spatial language abilities as well as the mapping between these abilities and analogous (non-spatial) verbal as well as (non-verbal) visuospatial abilities, from an adult-lifespan perspective. We showed in a large group of typically developing adults aged between 18 and 85 years that the newly developed spatial language measures are sensitive to age-related differences in generating words denoting spatial relations (SVF) naming static and dynamic spatial relations (SNT), in long-term memory recall for spatial descriptions presented from a route or a survey perspective (SVM), and in processing spatial descriptions from a third-person-centred and an environment-centred perspective (VCSRF). Meanwhile, our results yielded that core and higher cognitive operations in the (non-spatial) verbal domain are relatively resilient to ageing effects, confirming that spatial language abilities are more vulnerable to normal ageing processes. In addition, different aspects of core and higher cognitive operations in the (non-verbal) visuospatial domain appeared to decline with increasing age, although the onset and the magnitude of the declines depended on the subability examined.

The comprehensive consideration of the relative age-related changes in verbal and visuospatial abilities offers an important window regarding how spatial language is underpinned by these distinct types of cognition. From a theoretical point of view, the parallel adult-lifespan trajectories of spatial-verbal and (non-verbal) spatial abilities indicate that these two types of cognition are closely related and confirm that they are supported, at least to some extent, by overlapping networks in the brain, that are comparably affected by typical ageing processes. These findings are consistent with the hypothesis of a supramodal cognitive system supporting spatial processing operations. Moreover, our findings are not only theoretically important, but also have practical and clinical implications in terms of identifying the normal range of age-related changes in different spatial language abilities, which could be used as clinical markers of typical ageing while examining the neuropsychological profile of atypically ageing populations, such as patients with dementias.

The next part focuses on Alzheimer's disease (AD). Chapter 6 provides an overview of the main characteristics of AD, focusing on brain damage and cognitive deficits occurring during the early stages of the disease. Chapter 7 presents novel findings concerning spatial language production, memory, and comprehension in patients at an early stage of Alzheimer's disease. The impact of all studies conducted here, along with future directions are further discussed in the final chapter of the present thesis.

Part III

Alzheimer’s disease

Chapter 6 Introduction to dementia and Alzheimer's disease

6.1 Relevance and context

As the world's population is continuously getting older (Eurostat, 2015; UN, 2013), age-related disorders that affect cognition are becoming dramatically more frequent (Abbott, 2011; Alzheimer's Association, 2016; Brookmeyer et al., 2007; Hampel & Lista, 2016). It is estimated that around 35.6 million people live with dementia worldwide, with numbers expected to almost double every 20 years, and reach 65.7 million in 2030 (Prince et al., 2013) and 131 million by 2050 (Abbott, 2011). In the UK alone, there are currently over 850,000 people living with dementia – that is 1.3% of the entire UK population and 7.1% of the population aged 65 or more (Prince et al., 2014), while the number of patients with dementia is projected to exceed one million by 2021 and two million by 2051 (Matthews et al., 2013). It is estimated that the annual cost of dementias to the NHS, local authorities, and patients' families is about £26 billion, nearly twice that of cancer (£12 billion) and far more than the costs of heart disease (£8 billion) and stroke (£5 billion) (Prince et al., 2014).

Dementia is a clinical multi-component syndrome characterised by cognitive decline that significantly impairs capacity for independent living. There are various aetiological factors that may lead to dementia, such as neurological (e.g., Huntington's disease, Creutzfeldt Jakob disease, amyotrophic lateral sclerosis), psychiatric (e.g., major depression disorder, schizophrenia), endocrinological (e.g., Cushing syndrome, hypothyroidism, adrenal insufficiency), metabolic (e.g., hepatic insufficiency), traumatic (e.g., chronic traumatic encephalopathy), infectious (e.g., HIV infection, neurosyphilis), nutritional (e.g., B_{12} or thiamine deficiency), or toxic (e.g., exposure to heavy metals, drug/medication intoxications). However, neurodegenerative conditions, such as Alzheimer's disease (accounting for the 62% of dementia cases), cerebrovascular pathologies (17-25% of dementia cases), Lewy body pathology (6-10% of dementia cases), and frontotemporal lobar degeneration (2-4% of dementia cases), are the most common underlying pathologies leading to dementia (Prince et al., 2014). Other neurodegenerative conditions, such as Parkinson's disease, corticobasal syndrome, and progressive supranuclear palsy, may also lead to dementia, however, in these conditions motor symptoms are typically present years before dementia onset. Different types of dementia are associated with distinctive brain abnormalities and relatively differentiable symptom patterns in the early stages, before the disease process has become so widespread as to obliterate them.

6.2 Alzheimer's disease

6.2.1 Risk factors, characteristics, and diagnostic criteria

Alzheimer's disease (AD) is the most prevalent cause of chronic dementia. AD exists in both familial and sporadic forms. Familial forms are caused by single genes mutation that are inherited in an autosomal-dominant way and account for about 4-5% of cases (Alzheimer's Association, 2015). Sporadic forms have a multifactorial aetiology, in which some genetic polymorphisms are known to act as predisposing factors. Apolipoprotein E (APOE) has been recognized as the major genetic risk factor for late onset AD (i.e., after the age of 65) (Liu, Kanekiyo, Xu, & Bu, 2013; Yu, Tan, & Hardy, 2014).

The pathogenesis of sporadic AD remains unclear, however, several vascular, lifestyle, psychological and genetic risk factors for AD have been recognized to act both independently and by potentiating each other. Old age and presence of disease-predisposing genetic polymorphisms are the most important risk factors. Other recognized risk factors for developing AD include cerebrovascular pathology (Arvanitakis et al., 2016; Di Marco et al., 2015), traumatic brain injury or chronic traumatic encephalopathy (Washington, Villapol, & Burns, 2016) and immunological processes in the brain characterized by release of inflammatory mediators (Heneka et al., 2015), history of depression (Diniz, Butters, Albert, Dew, & Reynolds, 2013) and lack of social interaction (Kuiper et al., 2015), low education (Katzman, 1993; Ngandu et al., 2007; Wang et al., 2012), and certain dietary habits, such as increased consumption of saturated and trans fats (Barnard et al., 2014; Morris & Tangney, 2014).

The key pathophysiological changes observed in the brain tissue of AD patients are the accumulation of extraneuronal plaque deposits of the amyloid-β peptides and deposits of intraneuronal neurofibrillary tangles caused by abnormal hyperphosphorylation of the microtubule binding tau proteins (Lewczuk, Mroczko, Fagan, & Kornhuber, 2015). Additional changes include reactive microgliosis, loss of neurons and white matter, and synaptic dysfunction, while cerebrovascular pathologies, such as ischemic or white matter lesions, may contribute to the clinical syndrome of AD (Thal, Attems, & Ewers, 2014) or to the development of mixed dementia (De Reuck et al., 2016).

The rate of AD progression varies greatly between individuals. Interindividual variability in cognitive impairment has been associated with the progression of AD pathophysiology (Jack et al., 2013). Nevertheless, AD typically progresses insidiously with a slow presymptomatic course that can last years before symptoms are evident (Sperling, Mormino, & Johnson, 2014) and then progresses into three general symptomatic stages – mild (early-stage), moderate (middle-stage), and severe (later-stage). Nevertheless, during the prodromal stages of AD, individuals often report a self-experienced subtle decline in cognitive capacity compared to previous status (Jessen et al., 2014), especially subjective memory impairment (Jessen et al., 2010).

Cell loss tends to originate in the hippocampus and entorhinal cortex of the medial temporal lobe. Tau-positive neurofibrillary tangles and amyloid-β plaques then spread to lateral and basal temporal lobe and medial parietal cortex, therefore, there is disproportionate temporo-parietal atrophy during the early stages of AD (Frisoni, Fox, Jack, Scheltens, & Thompson, 2010; Harper et al., 2017). The primary motor and sensory cortical regions are generally spared. The continuing disease processes then spread to frontal areas, while at the later stages of AD that are characterised by severe global cognitive decline, there is widespread brain atrophy (Masters et al., 2015).

As definite diagnosis of AD is based on biopsy or autopsy, the clinical diagnosis of AD is typically qualified as probable or possible. The standard criterion for a diagnosis of probable AD is gradual progressive cognitive decline in two or more cognitive domains, that interferes with social or occupational functioning or managing usual activities, in the absence of disturbances in consciousness (delirium) or a medical, neurological, or psychiatric condition that could account for the cognitive decline (McKhann et al., 2011). One of the areas of cognitive impairment must be an inability to learn new information or recall recently learned information (McKhann et al., 2011) even in paradigms that involve retrieval facilitation with cueing (Dubois et al., 2014). There should also be evidence of cognitive dysfunction in at least one other cognitive domain, including visuospatial abilities, language functions, reasoning and executive functioning, or changes in personality, mood, and behaviour (McKhann et al., 2011). Differential diagnosis of probable AD dementia should be applied in cases with substantial cerebrovascular disease, defined by a history of stroke temporarily related to the onset of cognitive impairment or the presence of multiple or extensive infarcts, prominent features of dementia with Lewy bodies or frontotemporal dementia, and evidence for another medical condition or use of medication that could substantially affect cognitive functioning (Dubois, 2014; McKhann et al., 2011).

Biomarker evidence supportive of AD include (1) disproportionate temporoparietal atrophy on MRI, (2) decreased glucose metabolism in temporoparietal regions on fluorodeoxyglucose (FDG) PET, and (3) cerebrospinal fluid analysis of amyloid-β and tau (total tau or phosphorylated tau) concentrations (Jack et al., 2013). Biomarker evidence may increase the certainty that the basis of the clinical dementia syndrome is the AD pathophysiological process, however, there are several limitations in including them in routine diagnostic assessments, predominantly due to the lack of standardization of reliable criteria, and, additionally, due to the limited access to certain biomarkers that can be examined port-mortem (Albert et al., 2011; McKhann et al., 2011). Furthermore, biomarker results may be ambiguous, or identify "positive" findings that imply the presence of the underlying AD pathophysiological process in individuals who do not present clinical symptoms, or negative findings that unequivocally imply absence of the underlying AD pathophysiological process (McKhann et al., 2011). Importantly, post-mortem and amyloid imaging studies have consistently shown that β-amyloid aggregation is commonly observed in the brains of clinically normal older individuals (individuals who do not exhibit cognitive impairment) (for a review see Mormino, 2014). Amyloid burden in cognitively intact older adults has been associated with heightened atrophy in the frontal, parietal, and temporal cortices (Oh et al., 2013). On the other hand, the core clinical criteria provide very good diagnostic accuracy and utility, and to make a diagnosis of probable AD dementia with biomarker support, the core clinical symptoms must first be satisfied (McKhann et al., 2011).

Despite intense research and clinical efforts over many years, there is currently no cure for AD. Available pharmacological treatments (including acetylcholinesterase inhibitors and N-methyl d-aspartate receptor antagonists) provide limited symptomatic relief as they target established neuropathological features of AD, while the lack of understanding of the pathogenic processes of the disease hinders the development of effective treatments that can prevent the onset and progression of the disease (Kumar & Singh, 2015).

Early and accurate diagnosis, however, may result in economic benefits for both patients and society (Leifer, 2003) and can offer patients a better chance in preparing and planning for the future early on as well as in receiving earlier and targeted support and treatment that may help in slowing down the progression of the symptoms (Fox et al., 2013). As discussed, the diagnostic criteria for AD rest on the development of deteriorating cognitive deficits that impair daily functioning. Therefore, a probable clinical diagnosis of AD is primarily based on cognitive and behavioural evaluation, with accompanying medical and imaging testing used to rule out other possible conditions that could result in dementia.

This highlights the importance of interdisciplinary approaches to primary care for people with dementia and the role of neuropsychological assessment, which can help establish the presence or absence of cognitive deficits as well as the nature and the extent of these deficits, contribute to accurate differential diagnosis, and formulate intervention designs that target the patient's psychosocial needs (Clare, 2008; Fox et al., 2013).

6.2.2 Cognitive functioning

AD typically begins insidiously and progresses slowly. The disease involves a wide spectrum of clinical presentations (for reviews of the neuropsychological profile of AD see Salmon & Bondi, 2009; Weintraub, Wicklind, & Salmon, 2012) that generally follow neuronal and synaptic loss occurring initially in the entorhinal cortex and hippocampus and subsequently in associative temporo-parietal regions (Harper et al., 2017; Shi, Liu, Zhou, Yu, & Jiang, 2009). The extent of cognitive impairment and dementia severity parallels the extent of neocortical neuropathological changes (for a review, see Nelson et al., 2012). The sequence in which cognitive functions first show deterioration generally begins with episodic memory, while deficits in visuospatial abilities, executive functioning, and language are also prominent clinical presentations. After the initial appearance of amnesic symptoms, cognitive deterioration may be detained for up to three years (Haxby, et al., 1992). However, as the disease progresses, cognitive impairment becomes broader and the rate of decline gradually accelerates. Patients with moderate disease severity exhibit some level of impairment on almost all cognitive tasks (Caccappolo-Van Vliet et al., 2003). Late in the disease course, there is general loss of cognitive functions, with aphasia, apraxia, and various agnosias becoming prominent problems. In a very general sense, the pattern of functional regression has been considered as the inverse of normal developmental stages (Emery, 2000). The focus here will be on the characteristics of the early stages of AD with mild dementia severity.

Memory. The hallmark clinical symptom of AD is slow, progressive impairment in episodic memory, characterized by deficits in the acquisition and retrieval of recently learned information (Galton, Patterson, Xuereb, & Hodges, 2000; Ivanoiu et al., 2005; for review see Gallagher & Koh, 2011). Recent advances in neuroimaging offer the opportunity to investigate the progressive disruption of functional and structural networks over the course of AD (Chhatwal et al., 2013; Myers et al., 2014; Petrella et al., 2011). The topographic evolution of the pathophysiological processes of AD, detected by PET amyloid imaging, initially targets brain regions of high connectivity, designated as "cortical hubs" (Buckner et al., 2009). These brain regions overlap specific brain networks, including the default mode network (Buckner et al., 2005; Lustig et al., 2003) that project heavily to the medial temporal lobe system (for a review, see Sperling et al., 2010), thought to play a key role in both memory encoding and retrieval processes. Disruption of the intrinsic connectivity of these networks in AD patients has also been observed during resting state (Greicius, Srivastava, Reiss, & Menon, 2004; Supekar et al., 2008; Wang et al., 2006, 2007; Zhou et al., 2008). In addition, numerous functional neuroimaging studies have reported functional abnormalities in these regions during memory tasks (e.g., Celone et al., 2006; Maestu et al., 2003; Sperling et al., 2003), employing either verbal (e.g., Rémy, Mirrashed, Campbell, & Richter, 2005) or visuospatial (e.g., Rombouts et al., 2005) stimuli (for meta-analysis see Schwindt & Black, 2009; Terry, Sabatinelli, Puente, Lazar, & Miller, 2015; for a review see Dickerson & Sperling, 2008).

Subtle deficits of verbal (Backman, Small, & Fratiglioni, 2001; Lim et al., 2014) and nonverbal (Iachini et al., 2009) anterograde episodic memory appear in very mild or preclinical stages of AD. Numerous studies have consistently shown that patients with AD exhibit substantial impairments on episodic memory tests of various cognitive procedures (e.g., free recall, recognition, paired-associate learning) across different modalities (e.g., auditory, visual) and information (e.g., verbal, visuospatial) (for reviews see Didic et al., 2011; Koen & Yonelinas, 2014). Changes in episodic verbal memory, typically assessed with list-learning tasks or free recall tasks of short stories, are evident even before structural changes become apparent in MRI (Jedynak et al., 2015), and seem to be more robust predictors of progression from mild cognitive impairment to AD than other biomarkers such as cortical thickness (Gomar et al., 2011). Longitudinal studies corroborate that preclinical AD selectively impairs episodic memory recall and recognition, while core short-term and working memory abilities are less affected (Albert, Moss, Tanzi, & Jones, 2001; Backman et al., 2001; for a meta-analysis see Backman, Jones, Berger, Laukka, & Small, 2005), reflecting the damage occurring initially in the hippocampal formation (Villemagne et al., 2013) and the compromised interconnectivity between medial temporal lobe regions and neocortical areas (Sperling et al., 2010).

The extent of retrograde amnesia in AD may present a temporal gradient, with remote events less affected compared to recent ones during the early stages of the disease (Sadek et al., 2004; Sagar, Cohen, Sullivan, Corkin, & Growdon, 1998), although some studies have failed to find similar life-epochs effects (e.g., Irish et al., 2011). This temporal gradient may reflect that, while the entorhinal cortex and hippocampus are essential for the acquisition and consolidation of new memories, long-term memories are supported by a wider multifocal neocortical network (Squire & Alvarez, 1995). Moreover, as in typical ageing, where the content of autobiographical memories shifts from episodic to semantic (Piolino et al., 2002), an episodic-to-semantic shift may become further pronounced in AD (Meulenbroek et al., 2010), perhaps as a compensation to the compromised episodic memory capacity. Moreover, disturbances in prospective memory (i.e., the ability to remember to perform a planned action at a future point in time [McDaniel & Einstein, 2011]) are common manifestations of AD (Dermody, Hornberger, Piguet, Hodges, & Irish, 2016; Duchek, Balota, & Cortese, 2006) and have been associated with episodic memory dysfunction and the degradation of a distributed network of the brain involved in memory (Dermody et al., 2016; for a review on future-oriented thinking in neurodegenerative syndromes, see Irish & Piolino, 2015).

Language and semantic knowledge. While certain domains of language remain intact until late stages of AD, several expressive and receptive language functions start to decline early in the course of the disease in a significant proportion of AD patients (for reviews see Szatloczki et al., 2015; Taler & Phillips, 2008; Verma & Howard, 2012). While deterioration in the quality, quantity, and meaningfulness of verbal production and comprehension is primarily thought to result from declines in semantic levels of language processing, language impairment may also be influenced by other symptoms, such as concentration and executive deficits. Moreover, episodic memory dilapidation can substantially hamper the quality of verbal communication (Dijkstra, Bourgeois, Allen, & Burgio, 2004), as AD patients tend to regularly repeat themselves and have difficulties in following a conversation string. Nevertheless, the basic mechanical principles of language, such as syntax and lexical structure and articulation, appear to remain well preserved in AD patients (Croot et al., 2000).

In the earliest stages of AD, subtle language deficits involve word-finding and lexical retrieval difficulties (Blair, Marczinski, Davis-Faroque, & Kertesz, 2007; Mendez, Clark, Shapira, & Cummings, 2003), poorer verbal fluency (Henry, Crawford, & Phillips, 2004; Murphy, Rich, & Troyer, 2006), and diminished comprehension with increased syntactic and grammatic complexity (Tsantali, Economidis, & Tsolaki, 2013). Progressive disintegration of semantic memory becomes evident once the neuropathology of the disease spreads to the temporal, frontal and parietal association neocortex (Adlam, Bozeat, Arnold, Watson, & Hodges, 2006; Rogers & Friedman, 2008; for review see Hodges & Patterson, 1995). Patients with mild dementia often perform poorly on tests reflecting semantic processing (e.g., Hodges, Salmon, & Butters, 1992; Joubert et al., 2010; Rogers, Ivanoiu, Patterson, & Hodges, 2006). These include picture-confrontation naming of objects (e.g., Faust, Balota, & Multhaup, 2004; Balthazar et al., 2008; Lin et al., 2014) and verbal fluency (Raoux et al., 2008; Tierney, Yao, Kiss, & McDowell, 2005; for meta-analyses and reviews, see Henry, Crawford, & Phillips, 2004; Laws, Duncan, & Gale, 2010), as well as semantic categorization (Aronoff et al., 2006) and matching conceptually related pictures (Peraita, Diaz, & Anello-Vento, 2008).

The underlying nature of these lexico-semantic deficits has been debated as to whether they result from deterioration in the structure and content of semantic knowledge or from impaired operations of effortful access and retrieval of semantic information. The fact that AD patients consistently perform poorly across different tasks requiring semantic processing, including semantic categorization (Aronoff et al., 2006) or matching conceptually related pictures (Peraita et al., 2008), has led to the assumption that these deficits emerge from semantic degradation. However, studies using lexical-decision priming paradigms have found intact semantic priming effects for certain types of semantic relationships (i.e., category superordinates [e.g., *apple-fruit*] and coordinates [e.g., *cherry-apple*]) in AD patients, despite their poor performance in explicit semantic memory tasks, suggesting that their semantic deficits emerge from deficient explicit retrieval in combination with a partially degraded semantic network (Rogers & Friedman, 2008). In line with this, semantic impairment in AD patients has been associated with cortical atrophy in the anterior temporal lobe and inferior prefrontal cortex (Joubert et al., 2010). AD patients exhibit impaired attribute semantic priming (Rogers & Friedman, 2008), particularly for distinctive attributes (e.g., *stripes-zebra*) compared to shared attributes (e.g., *duck-feathers*) (Laisney et al., 2011). These findings, in accordance with distributed models of semantic representations, support a gradual hierarchic semantic deterioration in AD, where loss of distinctive attribute knowledge (Catricalà et al., 2015) causes close concepts to merge (e.g., *zebra-horse*). As concepts lose their distinctiveness, thinking may become more vague and communication may become poorer in content.

Visuospatial cognition. Patients at an early stage of AD typically display impaired visuospatial abilities, as demonstrated by several different means involving both small and larger scales of space. Studies involving figural space using paper-and-pencil tasks that require integration of visual information have reported impaired visuospatial perception (e.g., Simard, van Reekum, & Myran, 2003; Quental, Brucki, & Bueno, 2013), visuoperceptual organization (Paxton et al., 2007), and visuoperceptual discrimination (Alegret et al., 2009) abilities, as well as poorer ability of mentally rotating objects (Lineweaver, Salmon, Bondi, & Corey-Bloom, 2005). Impairments in visuoconstructional abilities, such as clock drawing

(Leyhe et al., 2009) or copying complex figures (Serra et al., 2010) are also well documented in AD patients.

The deterioration of visuospatial perception abilities during the amnesic preclinical stages of AD seems to be attributable to alterations in the connectivity of fronto-parieto-temporal regions as well as functional alterations in these regions (Jacobs et al., 2015). Marked widespread neuronal dysfunction, extending the hippocampus, has also been reported in amnesic prodromal AD patients during encoding of object-location binding associations (Hampsted, Stringer, Stilla, Amaraneni, & Sathian, 2011). Furthermore, several studies with AD patients have shown impairment on dorsal stream functions, such as motion perception (Mapstone, Dickerson, & Duffy, 2008; Thiyagesh et al., 2009) and spatial location matching (Bokde et al., 2010).

Visuospatial impairments among AD patients also occur in larger-scale space. Brief episodes of spatial disorientation or getting lost in familiar surroundings are among the earliest manifestations of AD (Monacelli, Cushman, Kavcic, & Duffy, 2003; Pai & Jacobs, 2004; Serino & Riva, 2013), consistent with the neuropathological impact of the disease on the medial temporal lobes and parietal cortex. Apart from spatial disorientation in familiar environments, patients with mild AD also display poor navigation abilities in new environments and are deficient at learning the locations of landmarks, as demonstrated by route-learning tasks (e.g., Cushman et al., 2008; Rankin, Mucke, Miller, & Gorno-Tempini, 2007; Tu et al., 2015; Tu, Spiers, Hodges, Piguet, & Hornberger, 2017; Yew, Alladi, Shailaja, Hodges, & Hornberger, 2013). Spatial orientation impairments have been attributed to atrophy of the right posterior hippocampal and parietal areas (Rankin et al., 2007), as well as the retrosplenial cortex (Tu et al., 2015), which is considered to be a neural hub with multiple projections to occipital, temporal, and parietal lobe structures and thus playing a critical role in processing and integrating visuospatial information in order to construct internal representations of space (Iaria, Chen, Guariglia, Ptito, & Petrides, 2007; Rao, Zhou, Zhuo, Fan, & Chen, 2003; Vann, Aggleton, & Maguire, 2009). AD-associated deficits in spatial orientation and navigation have been observed in tasks requiring both egocentric- and allocentric-based representations (e.g., Cherrier, Mendez, & Perryman, 2001; Cushman et al., 2008; Moodley et al., 2015; Hort et al., 2007; Tu et al., 2015, 2017; Weniger et al., 2011).

Chapter 7 Spatial language in early Alzheimer's disease (3rd series of studies)

7.1 Objectives and hypotheses

Several lines of evidence support the notion that the neuropathological changes associated with AD are occurring possibly several years or decades before experiencing the cognitive and functional changes associated with the disease. Meanwhile, the development of disease modifying therapeutic agents requires reliable identification of patients when neuropathological changes are minimal. Despite recent advances in developing in vivo structural and molecular neuroimaging and cerebrospinal fluid biomarkers, the absence of a reliable and readily available biomarker of AD places cognitive assessment at the centre in the identification and clinical diagnosis of AD. Not surprisingly, many clinicians have been advocating that screening measures should be introduced in primary care clinical settings to enable early detection of dementia (for a discussion, see Brayne, Fox, & Boustani, 2007). There is therefore a clear need for more sensitive measures for the detection of subtle cognitive and functional changes emerging at the earliest or even at pre-symptomatic stages of the disease (Snyder et al., 2014). Identifying which aspects of cognition are affected in people with AD is important not only for accurate and differential early diagnosis and staging of the condition, but it also enables patients, caregivers, and clinicians to better understand the nature and the extent of the difficulties they might experience in everyday activities and take decisions for the future early on. Importantly, the early detection of AD cases may also offer scientists a better chance to understand AD pathogenesis, which in turn could impact future development of treatment strategies.

Memory impairment is the hallmark of AD symptomatology (for reviews see Didic et al., 2011; Koen & Yonelinas, 2014) and has great diagnostic value, however, significant memory declines are also apparent in various other dementia syndromes, such as frontotemporal dementia (e.g., Hornberger et al., 2010), which can lead to diagnostic uncertainty. Therefore, in clinical practice, comprehensive neuropsychological assessments should also include measures that can help in differential diagnosis and staging the severity of dementia. As discussed earlier, a large number of recent studies has identified significant deficits in visuospatial cognition in AD patients (for reviews see Lithfous, Dufour, & Despres, 2013; Iachini et al., 2009; Serino, Cipresso, Morganti, & Rova, 2014; Vlček &

Laczó, 2014), such as spatial disorientation (e.g., Monacelli et al., 2003; Tu et al., 2015, 2017; Yew et al., 2013). Visuospatial deficits occur at the earliest stages of AD, and even at prodromal stages of AD such as mild cognitive impairment (Cushman et al., 2008), reflecting neurodegenerative changes in medial temporal and parietal lobes. In fact, a recent study showed that non-demented individuals at risk of developing AD exhibit poorer performance on visuospatial tasks compared to matched individuals with free familial history of AD (Ritchie et al., 2017).

While deficits in visuospatial cognition amongst patients with AD are well documented, there is considerable lack of knowledge regarding their ability to process and communicate spatial information with verbal means. The main purpose of the present studies is to experimentally investigate various aspects of spatial language processing in individuals who are at an early stage of AD, for the first time. Communicating spatial information with verbal means (for example describing the location of an object or comprehending verbal directions in order to reach a destination) represents a core part of human communication in various everyday settings. Despite its importance, spatial language has never been systematically studied in people with AD. Spatial language forms a natural bridge between verbal and non-verbal (visual-spatial) abilities. Interfacing linguistic and spatial representations involves operations of transformation of information, translated from a spatial representation to a linguistic format, and vice versa. This unique characteristic of combining and translating information from different modalities (verbal and visuospatial) in the context of communication may prove particularly challenging for people with AD.

After having identified the trajectories of decline in spatial language abilities in typical ageing (Chapter 5), we next sought to examine potential deficits in aspects of spatial language production, spatial-verbal memory, and comprehension under different spatial reference frames in patients at an early stage of AD. The results will enrich our knowledge of the cognitive profile of AD patients, and may lead to the identification of markers of atypical ageing that could be used clinically for earlier and more accurate diagnosis of AD and subsequently provide a basis for future intervention designs. On the grounds of parallel trajectories of age-related decline in (non-verbal) visuospatial and spatial-verbal abilities revealed in typical ageing (Chapter 5), it is expected that spatial-verbal processing will be impaired in AD patients. Taking into account the well-established visuospatial deficits among AD patients, a concurrent impairment in linguistic representations of space would further support the hypothesis of a supramodal cognitive system supporting spatial processing.

7.2 Methods

7.2.1 Participants

Data obtained from 17 patients at an early stage of Alzheimer's disease, ranging in age from 65 to 87 years, and 21 age-, education-, and gender-matched healthy controls were used for the present studies. All patients were diagnosed with probable AD within a two-year period prior to participation. All patients fulfilled international consensus criteria for AD (McKhann et al., 2011) and their clinical diagnoses were established by clinical staff of the clinics of the Norfolk and Suffolk NHS Foundation Trust (NSFT), located in East Anglia, UK, based on clinical interviews, formal cognitive assessments, and medical examinations.

Participants who did not speak English as their first language were excluded from the study. Individuals at a later stage of AD (having been diagnosed with probable AD within a period greater than two years prior to participation) were excluded from participation. The MoCA (Nasreddine et al., 2005) screening test was administered to each participant at the beginning of the testing session, in order to assess their general cognitive functioning. According to past research, the MoCA score for mild AD ranges from 11 to 21 (Nasreddine et al., 2005). Hence, a score lower than 11 would be suggestive of severe dementia, and data of individuals with scores lower than 11 were excluded from the study. Furthermore, individuals who have had a diagnosis of other types of neurodegenerative disorders (such as dementia with Lewy Bodies, Parkinson's disease, Huntington's disease, or progressive supranuclear palsy) or other disorders of the central nervous system that could severely affect cognitive functioning, such as brain tumours, (non-transient) stroke, multiple sclerosis, normal pressure hydrocephalus, toxic conditions such as substance abuse/dependence, or infectious processes such as HIV and encephalitis were not eligible to participate. Finally, individuals with a history of schizophrenia or another psychotic disorder, or severe learning or intellectual disabilities were excluded from participation.

All participants had normal or sufficiently corrected vision and hearing (by visual and/or hearing aids). Participants' demographic characteristics and MoCA scores are provided in Table 28.

Table 28. *Participants' Demographic Characteristics and MoCA Scores by Group*

	Group		
	AD	Controls	Group effect
N	17	21	-
Age (years)	77.4 (1.5)	77.6 (1.3)	n/s
Education (years)	11.1 (2.6)	11.5 (2.1)	n/s
Sex (% females)	53%	61%	n/s
Handedness (% right)	82.4%	95.2%	n/s
Hearing loss	64.7%	52.4%	n/s
Vision loss	76.5%	76.2%	n/s
Medications (number)	4.3 (0.4)	2.1 (0.4)	**
MoCA (total/30)	16.3 (2.3)	27.1 (1.5)	**
Visuoconstruction (/5)	2.5 (1.3)	4.1 (0.9)	**
Verbal Memory (/5)	0.4 (0.7)	3.4 (0.8)	**
Attention (/6)	4.2 (1.0)	5.5 (0.6)	**
Orientation (/6)	3.7 (1.1)	5.9 (0.2)	**

Note. Values represent means (and standard deviations); MoCA = Montreal Cognitive Assessment; n/s = not significant; $^{**}p < .001$.

7.2.2 Ethics

All study procedures were ethically approved by the Research and Enterprise Office of the University of East Anglia, the Research Governance Committee of the Norfolk and Suffolk NHS Foundation Trust, and the Essex Research Ethics Committee of the Health Research Authority of the NHS. All experimental procedures were in compliance with the Good Clinical Practice guidelines of the NHS and the ethical guidelines of the British Psychological Society.

7.2.3 General procedure

Participants of the patient group were identified and recruited with the help of staff members of the Norfolk and Suffolk NHS Foundation Trust. Testing took place in a suitable room at the University of East Anglia or at the patient's homes when required, on an individual (one-to-one) basis in a single session lasting approximately 60 minutes, with breaks taken whenever required. At the outset of each session, patients completed a semi-structured interview providing detailed health and demographic information with the help of their caregiver. All participants were administered the MoCA screening test (Nasreddine et al., 2005) to assess overall cognitive function, followed by the novel battery of spatial language tests assessing production, memory, and comprehension, along with their analogous non-spatial verbal tests when appropriate (see next Section). All tasks were presented in a printed format and were administered in a semi-randomized order.

Each patient participated voluntarily and provided written informed consent for participating before testing, and received a monetary compensation of £10 at the end of the session.

Participants from the control group were selected from the large sample of participants used in the previous studies (see Section 5.2.1), in order to match the patients in age, gender, and education. The general procedure for testing controls is described in Section 5.2.2.

7.2.4 Measures

All participants were administered the battery of spatial language tests, along with their analogous non-spatial verbal tests when appropriate. This assessment included:

1) Naming spatial relations (Spatial Naming Test), objects (Boston Naming Test), and actions (Action Naming Test) (for descriptions of the naming tests see Sections 3.2.2 and 5.2.3.2).
2) Episodic memory (immediate and delayed recall) for route- and survey-based spatial descriptions (Spatial Verbal Memory task) and for non-spatial verbal information (Logical Memory) (for descriptions of the memory tasks see Sections 3.2.3 and 5.2.3.3).
3) Processing of locative spatial descriptions presented under different spatial reference frames, including self-centred, third-person-centred, object-centred, and environment-centred reference frames (Verbal Comprehension in Spatial Reference Frames task; for descriptions of this task see Sections 3.2.4 and 5.2.3.4)

7.2.5 Analysis procedures

Group differences in demographic characteristics and MoCA scores were examined with one-way analysis of variance (Table 28). Mixed factorial analyses of variance were employed to examine Group (between-subjects variable) and Test Condition (within-subjects variable) effects and their possible interaction effects on all measures considered. Significant main effects were followed up with Bonferroni-adjusted post hoc tests and significant interaction effects were followed up with Bonferroni-adjusted tests of simple main effects.

The discriminative validity of all tests considered for detecting AD when compared with controls was examined with binary logistic regression models and Receiver Operating Characteristic (ROC) curves of sensitivity (true positive rate, i.e., the ability of a test to correctly identify the patients) and specificity (true negative rate, i.e., the ability of the test to correctly identify the controls). A ROC curve is obtained by plotting all sensitivity values on the y-axis against their equivalent (1-specificity) values on the x-axis. The area under the curve (AUC), a single measure of overall test accuracy reflecting the proportion of correctly classified cases, was also calculated. AUC values closer to 1 indicate the test reliably distinguishes cases, whereas values at .5 indicate the predictor is no better than chance (Zhou, McClish, & Obuschowski, 2009).

7.3 Results

7.3.1 Episodic memory

7.3.1.1 Episodic memory performance

Performance based on the proportion of correctly recalled items in the immediate and delayed trials across the (non-spatial) verbal (Logical Memory), and route-based and survey-based spatial-verbal (Spatial Verbal Memory) memory tasks for the two groups is presented in Figure 27.

Immediate recall. A mixed 2 (Group: patients, controls) × 3 (Information Type: non-spatial verbal, route-based spatial-verbal, survey-based spatial-verbal) ANOVA yielded a significant main effect of Information Type, $F(2, 72) = 34.55$, $p < .001$, partial $\eta^2 = .49$, and Group, $F(1, 36) = 79.08$, $p < .001$, partial $\eta^2 = .69$, which were qualified by a significant interaction effect between the two factors, $F(2, 72) = 8.21$, $p = .001$, partial $\eta^2 = .19$. Analyses of simple main effects showed that the effect of Group was significant for the non-spatial verbal, $F(1, 36) = 81.55$, $p < .001$, $\eta^2 = .69$, and the route, $F(1, 36) = 40.82$, $p < .001$, $\eta^2 = .53$, and survey, $F(1, 36) = 37.10$, $p < .001$, $\eta^2 = .51$, spatial-verbal memory tasks. Pairwise comparisons with Bonferroni correction indicated that the patient group recalled significantly less survey information compared to route ($p = .024$) and non-spatial verbal information ($p = .006$), while the control group recalled significantly less survey information compared to non-spatial verbal information ($p < .001$).

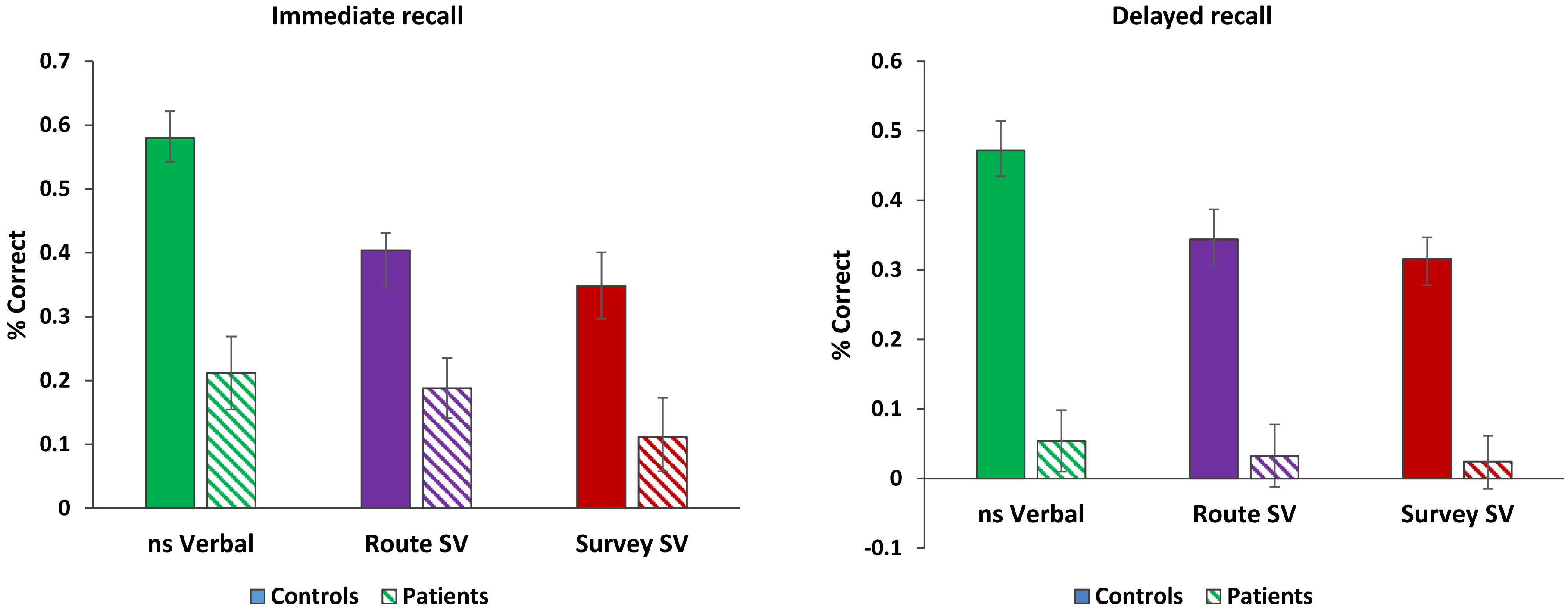


Figure 27. Episodic memory performance for (non-spatial) verbal descriptions (Logical Memory test), and route-based and survey-based spatial descriptions (Spatial Verbal Memory task), by group.
Note. Left panel: immediate recall, right panel: delayed recall; ns = non-spatial, SV = spatial-verbal; Error bars represent 95% confidence intervals; N = 38.

Delayed recall. A similar factorial ANOVA revealed a significant main effect of Information Type, $F(2, 72) = 23.46$, $p < .001$, partial $\eta^2 = .39$, and a large main effect of Group, $F(1, 36) = 229.43$, $p < .001$, partial $\eta^2 = .86$, as well as a significant interaction between the two factors, $F(2, 72) = 11.20$, $p < .001$, partial $\eta^2 = .24$, on delayed recall. Analyses of simple main effects showed that the effect of Group on delayed recall was large for all information types (non-spatial verbal: $F(1, 36) = 204.53$, $p < .001$, $\eta^2 = .85$; route: $F(1, 36) = 111.17$, $p < .001$, $\eta^2 = .75$, and survey, $F(1, 36) = 130.30$, $p < .001$, $\eta^2 = .78$). Pairwise comparisons with Bonferroni correction indicated that controls recalled significantly less information from the route and survey descriptions compared to non-spatial verbal descriptions ($p < .001$), while AD patients performed at floor levels across all conditions.

Although examination of possible qualitative errors during the recall trials was beyond the scope of the present analyses, it is worth mentioning that AD patients produced several errors in their responses. These errors included perseverations and prior-description intrusions – for example, in the route description they would say "the man was very poor and hungry" referring to the protagonist of the LM description. Moreover, there were confabulations in the responses of AD patients, such as producing irrelevant and/or false descriptions – for example, in the route description they would say "the man met up with some friends and they had tea together".

7.3.1.2 Episodic memory tasks as diagnostic predictors of AD

Sensitivity and specificity of immediate and delayed episodic memory capacity for non-spatial verbal, route and survey descriptions were compared using logistic regression and ROC curves. Performance scores (% correctly recalled items) on each memory condition were used as predictors of AD diagnosis. Analysis yielded that the regression model was statistically significant, $\chi^2(6) = 52.23$, $p < .001$, explained 100% (Nagelkerke R^2) of the variance in AD diagnosis, and correctly classified 100% of cases (17 out of 17 AD patients; 21 out of 21 controls). However, for the current model the tolerance and VIF values indicated multicollinearity problems between the predictor variables, especially for the delayed recall trials (immediate recall: VIF = 6.1, tolerance = .127; delayed recall: VIF = 11.1, tolerance = .09). Therefore, it can be concluded that tests of episodic memory capacity have strong predictive power regardless of the information type considered. Computation of ROC curves for all episodic memory measures as predictors of AD diagnosis (Figure 28) supported the interpretation of the logistic regression results. AUC values indicated that all episodic memory measures had a very high level of diagnostic accuracy, regardless the type of information examined (AUV range: .92 to 1.00, 95% CI range: .85 to 1.00, all $p < .001$).

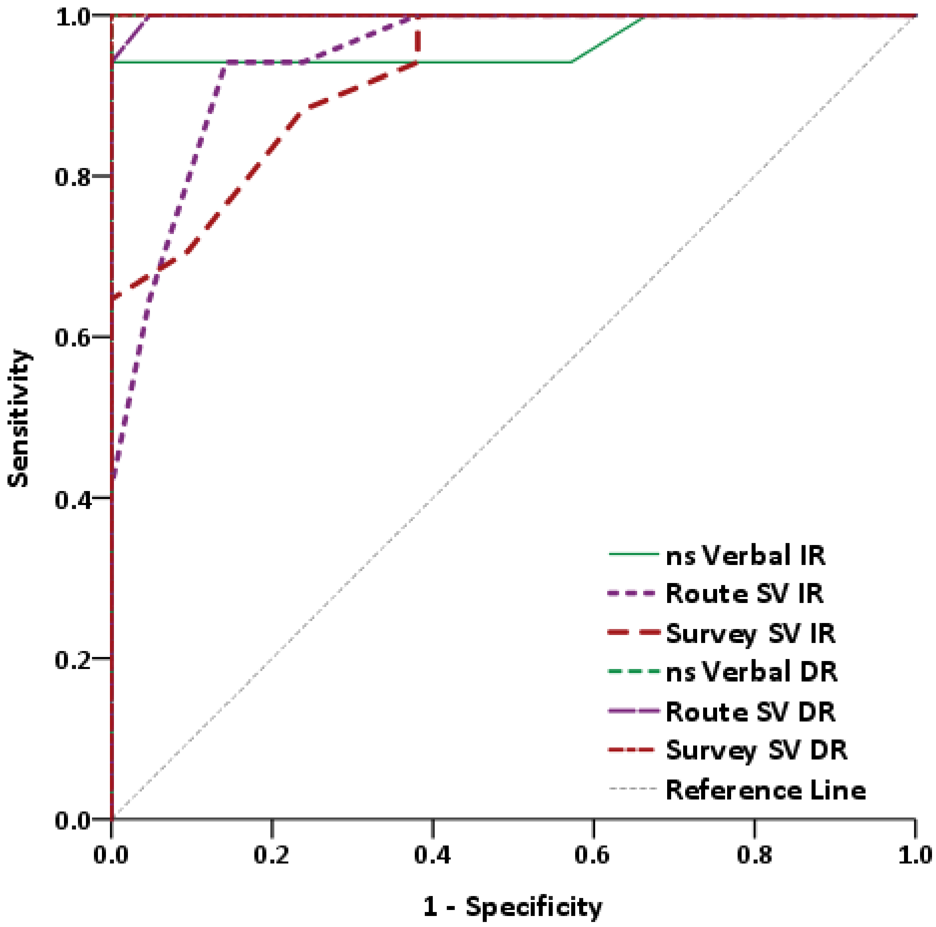


Figure 28. ROC curves for immediate and delayed recall of (non-spatial) verbal (Logical Memory test) and route- and survey-based spatial descriptions (Spatial-Verbal Memory task) in discriminating AD patients from controls.
Note. ns = non-spatial, SV = spatial-verbal, IR = immediate recall, DR = delayed recall; *N* = 38. We recommend readers view this figure in colour.

7.3.2 Naming

7.3.2.1 Naming performance

Performance based on naming accuracy (proportion of correct responses) across all naming tests (i.e., Spatial Naming Test, Boston Naming Test, Action Naming Test) for the two groups is presented in Figure 25. A mixed 2 (Group: patients, controls) × 3 (Naming Category: spatial relations, objects, actions) ANOVA yielded a significant main effect of Naming Category, $F(2, 72) = 49.39$, $p < .001$, partial $\eta^2 = .57$, as well as a main effect of Group, $F(1, 36) = 43.95$, $p < .001$, partial $\eta^2 = .55$, which were qualified by a significant interaction between the two factors, $F(2, 72) = 4.15$, $p = .020$, partial $\eta^2 = .10$. Analyses of simple main effects showed that the effect of Group on naming accuracy was particularly large for spatial relations, $F(1, 36) = 47.72$, $p < .001$, partial $\eta^2 = .57$, and its magnitude, although large, was lower for objects, $F(1, 36) = 22.37$, $p < .001$, partial $\eta^2 = .38$, and especially for actions, $F(1, 36) = 6.39$, $p = .016$, partial $\eta^2 = .15$. Pairwise comparisons with Bonferroni correction indicated that the patient group was less accurate in naming spatial relations compared to objects ($p < .001$) and actions ($p < .001$) and less accurate in naming objects compared to actions ($p = .045$). Similarly, controls were less accurate in naming spatial relations compared to objects ($p = .005$) and actions ($p < .001$), but their accuracy was comparable for object and action naming.

Although examination of qualitative errors in the naming tasks was beyond the scope of the present analyses, it is worth mentioning that AD patients often responded with spatial demonstratives (i.e., *here*, *there*) along with spatial deixis while completing the spatial naming task.

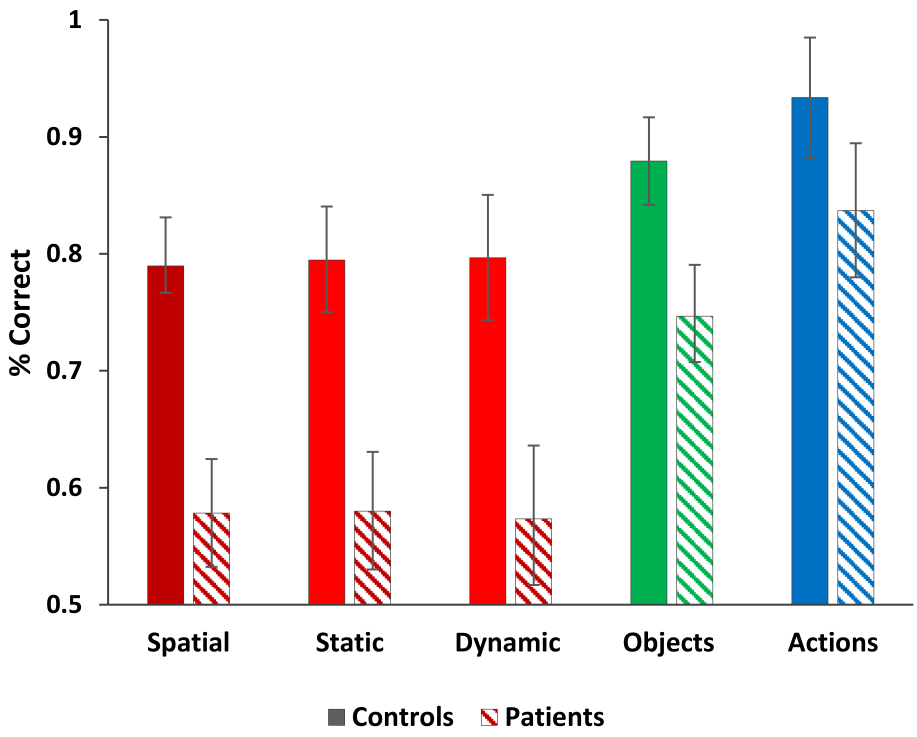


Figure 25. Naming accuracy (% correct responses) for spatial relations (Spatial Naming Test), objects (Boston Naming Test), and actions (Action Naming Test), by group. *Note*. Scores for spatial relations are presented separately for static and dynamic spatial relations, as well as composite scores. Error bars represent 95% confidence intervals; $N = 38$.

7.3.2.2 Naming tests as diagnostic predictors of AD

Sensitivity and specificity of performance on naming tests were compared using logistic regression and ROC curves. Accuracy scores (% correct responses) on each naming test were used as predictors of AD diagnosis. Analysis yielded that the regression model was statistically significant, $\chi^2(3) = 36.67$, $p < .001$, explained 83% (Nagelkerke R^2) of the variance in AD diagnosis, and correctly classified 92.1% of cases (15 out of 17 AD patients; 20 out of 21 controls). Spatial naming held a stronger level of predictive power ($\beta_{exp} = 2.63$, 95% CI for β_{exp} = 1.16 to 5.98, $p = .021$) compared to object naming ($\beta_{exp} = 1.84$, 95% CI for β_{exp} = .98 to 3.46, $p = .050$), while action naming did not significantly predict AD diagnosis ($\beta_{exp} = .86$, 95% CI for β_{exp} = .52 to 1.44, $p > .250$). For the current model, the variance inflation factor (VIF) values were all well below 10 (VIF = 1.54) and the tolerance statistics were all well above .2 (tolerance = .75) confirming that there was no issue of multicollinearity between predictors (Menard, 1995; Myers, 1990).

ROC curves were computed for all naming predictors in diagnosing AD patients (Figure 26). AUC values indicated that spatial naming (AUC = .93, 95% CI = .84 to 1.0) had a higher level of diagnostic accuracy than object naming (AUC = .89, 95% CI = .79 to .99), while action naming had relatively low discriminative capacity (AUC = .69, 95% CI = .51 to .86).

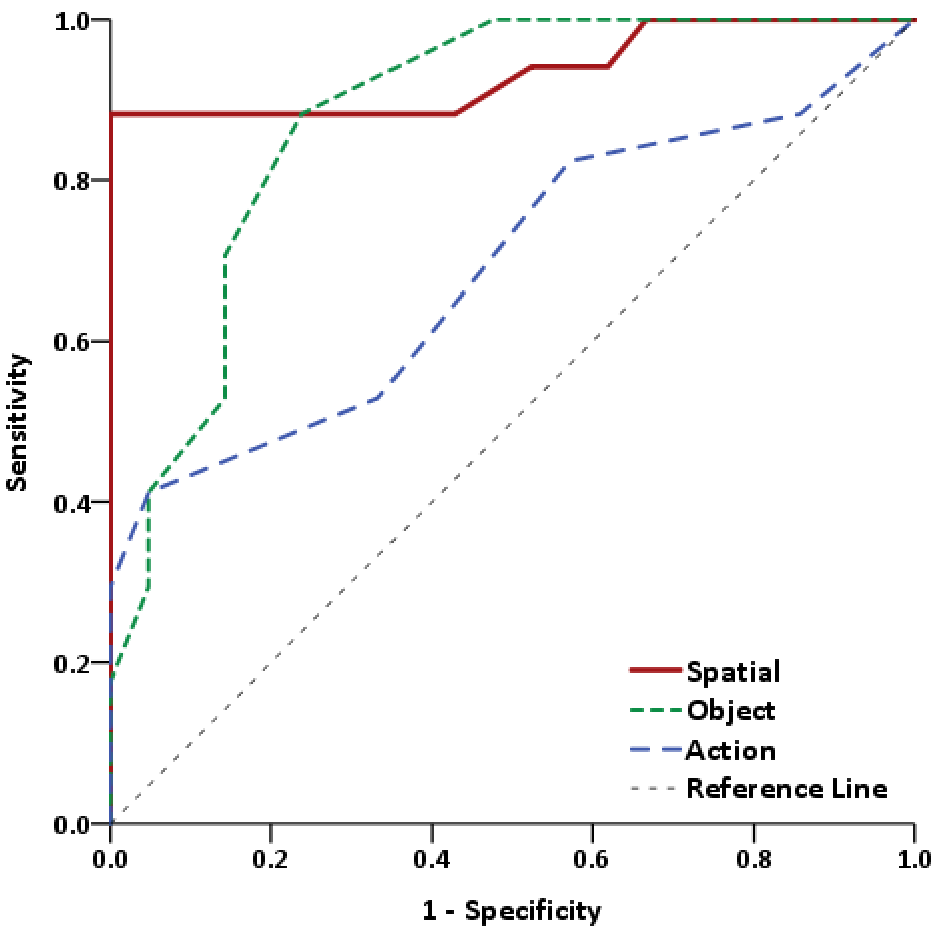


Figure 26. ROC curves for spatial (Spatial Naming Test), object (Boston Naming Test), and action (Action Naming Test) naming performance in discriminating AD patients from controls ($N = 38$). We recommend readers view this figure in colour.

7.3.3 Verbal comprehension in spatial reference frames (VCSRF)

7.3.3.1 Performance in the VCSRF task

Performance based on accuracy scores (proportion of correct responses) across all conditions of the VCSRF task (i.e., self-centred, third-person-centred, object-centred, and environment-centred frames) for the two groups is presented in Figure 29. Since performance at chance levels in the VCSRF task equivalates to a 50% accuracy score (as each response could be either true or false to judge each spatial statement), a closer inspection of Figure 29 can reveal that AD patients performed well above chance levels in the self- and object-centred conditions but close to chance levels in the third-person- and environment-centred conditions, while controls performed above chance levels across all conditions.

A mixed 2 (Group: patients, controls) × 4 (Frame: self-centred, third-person-centred, object-centred, environment-centred) ANOVA revealed a significant main effect of Frame, $F(3, 108) = 62.52$, $p < .001$, partial $\eta^2 = .56$, as well as a main effect of Group, $F(1, 36) = 45.18$, $p < .001$, partial $\eta^2 = .55$, with patients performing poorer than controls. The model also yielded a significant interaction between the two factors, $F(3, 108) = 4.86$, $p = .003$, partial $\eta^2 = .12$. Simple main effects analysis showed that the effect of Group was significant for all frames examined (self-centred: $F(1, 36) = 24.70$, $p < .001$, partial $\eta^2 = .41$; third-person-centred: $F(1, 36) = 59.45$, $p < .001$, partial $\eta^2 = .62$; object-centred: $F(1, 36) = 9.05$, $p = .005$, partial $\eta^2 = .20$; environment-centred: $F(1, 36) = 26.46$, $p < .001$, partial $\eta^2 = .42$). Follow-up pairwise comparisons showed that patients performed significantly poorer in the environment-centred frame compared to all other frames ($p < .001$) and poorer in the third-person-centred frame compared to the self-centred and object-centred frames ($p \leq .002$). Controls also performed poorer in the environment-centred frame compared to all other frames ($p < .001$) and significantly better in the self-centred frame compared to all other frames ($p \leq .036$).

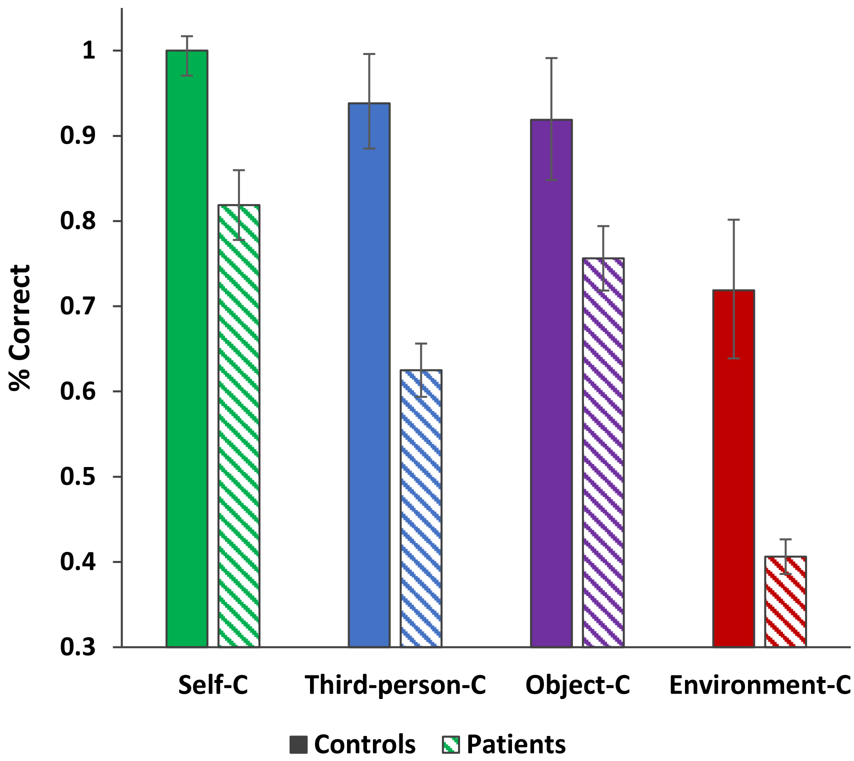


Figure 29. Performance based on accuracy (proportion of correct responses) under different spatial reference frames (Verbal Comprehension in Spatial Reference Frames task), by group. *Note*. C = centred; Error bars represent 95% confidence intervals; $N = 38$.

7.3.3.2 VCSRF task as diagnostic predictor of AD

Sensitivity and specificity of comprehension for descriptions of spatial relations under different spatial reference frames (i.e., self-centred, third-person-centred, object-centred, and environment-centred) were compared using logistic regression and ROC curves. Accuracy scores (% correct responses) on each spatial reference frame considered were used as predictors of AD diagnosis. Analysis yielded that the regression model was statistically significant, $\chi^2(4) = 52.26$, $p < .001$, explained 100% (Nagelkerke R^2) of the variance in AD diagnosis, and correctly classified 95% of cases (16 out of 17 AD patients; 20 out of 21 controls). Performance in the self-centred ($\beta_{exp} = 2.24$, 95% CI for $\beta_{exp} = 1.11$ to 4.97, $p = .002$) and third-person-centred frames ($\beta_{exp} = 2.91$, 95% CI for $\beta_{exp} = 1.52$ to 5.59, $p < .001$) held the strongest levels of predictive power, followed by performance in the environment-centred ($\beta_{exp} = 1.84$, 95% CI for $\beta_{exp} = 1.25$ to 2.71, $p = .005$) and object-centred ($\beta_{exp} = 1.51$, 95% CI for $\beta_{exp} = 1.08$ to 2.1, $p = .016$) frames. Tests of multicollinearity between the predictors for the current model indicated that the tolerance (.39) and VIF (2.7) values were within the acceptable range levels (Menard, 1995; Myers, 1990).

ROC curves were computed for scores across all VCSRF as predictors in diagnosing AD patients (Figure 30). AUC values indicated that performance in the third-person-centred frame (AUC = .96, 95% CI = .88 to 1.0) and the self-centred frame (AUC = .91, 95% CI = .81 to 1.0) had the highest level of diagnostic accuracy, followed by the environment-centred (AUC = .88, 95% CI = .77 to .99) and object-centred (AUC = .76, 95% CI = .61 to .91) frames.

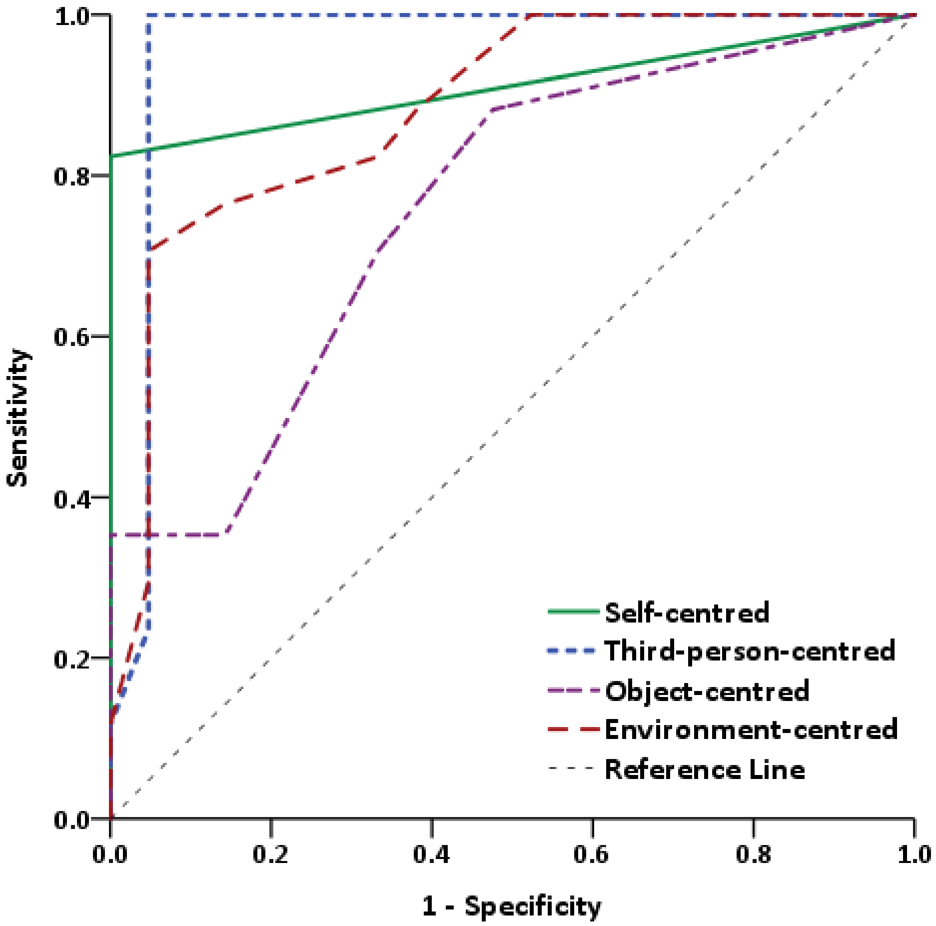


Figure 30. ROC curves for performance based on accuracy (proportion of correct responses) under different spatial reference frames (Verbal Comprehension in Spatial Reference Frames task) in discriminating AD patients from controls (*N* = 38). We recommend readers view this figure in colour.

7.4 Discussion

The present studies provided evidence confirming that patients at an early stage of AD exhibit significant impairments across different aspects of spatial language abilities. These include deficits in describing static or dynamic spatial relations between objects, severe deficits in short-term and long-term episodic memory capacity for spatial descriptions presented from a route or a survey perspective, and impairments in processing simple locative descriptions under different spatial reference frames. The present findings of impaired spatial language in mild AD, coupled with the well-established visuospatial deterioration reported in past research (Cushman et al., 2008; Hornberger et al., 2010; Tu et al., 2015), is further supporting the hypothesis of a supramodal system supporting internal representations of space, and corroborates our previous findings of simultaneous age-related effects on both linguistic and non-linguistic abilities of processing spatial information (Chapter 5). The findings regarding episodic memory, language production, and spatial-verbal comprehension in AD patients are discussed in turn below.

7.4.1 Episodic memory

Episodic memory capacity for newly-encoded verbal descriptions was particularly poor in AD patients, regardless the type of information considered (i.e., non-spatial verbal, and route- and survey-based spatial descriptions). All three episodic memory measures, including spatial-verbal memory for route or survey descriptions (spatial-verbal memory task) and non-spatial verbal descriptions (Logical Memory test), had similarly high levels of discriminative validity, both in terms of sensitivity and specificity, confirming the diagnostic value of episodic memory assessments in dementia.

The present findings extend the medial temporal lobe-associated anterograde memory deficits for verbal (Lim et al., 2014) and visuospatial (Iachini et al., 2009) information characterizing the early stages of AD to spatial descriptions, presented either from a static landmark-based survey perspective or from a dynamic person-centred route perspective. Effective encoding and retrieval of route descriptions requires monitoring the sequential change of locations along the route, while memory for survey descriptions involves object-location binding associations. Although the present study is the first one examining this kind of information type effects on verbal episodic memory in mild AD, previous studies have reported that AD patients exhibit marked impairments in verbally recalling a route they have learned either in real-world or virtual environments, suggesting loss of verbally mediated navigation capacities (Cushman et al., 2008). AD patients also exhibit widespread dysfunctions during spatial encoding for object locations (Hampstead et al., 2011) as well as impaired declarative spatial object-location memory (e.g., Kessels, Feijen, & Postma, 2005), both on recall of positional information (i.e., focusing on a location irrespective of object identity) as well as on recall of locations of different objects, requiring object-location binding operations (Kessels et al., 2010). Moreover, several studies, mostly using virtual routes, have shown significant deficits in route learning in patients at an early stage of AD, both from an allocentric or an egocentric spatial reference frame (Cherrier et al., 2001; Jheng & Pai, 2009; Moodley et al., 2015; Tu et al., 2015, 2017). According to Postma and colleagues (2008), object location memory involves not only object and spatial-location processing, but object-to-location binding processes as well. The medial temporal lobe and in particular the hippocampus have an essential role in supporting relational binding processes (e.g., Esfahani-Bayerl et al., 2016; Hannula & Ranganath, 2008; Koen et al., 2017; for a review see Postma et al., 2008; Yonelinas, 2013). It has been consistently found that AD patients display deficits in binding processes both for verbal (Parra et al., 2009) and visual (Parra et al., 2010) information (for a review on context memory see El Haj & Kessels, 2013), which can be attributed to hippocampal damage.

The episodic memory deficits among AD patients appeared to be considerably larger after an approximately 30-minute interval from the time of encoding compared to immediate recall. This is not surprising since delayed recall of verbal and visuospatial material typically deteriorates to floor levels even at the earliest stages of the disease, thus, immediate recall tasks may be better for staging dementia severity because they show a more linear decline (Lezak et al., 2012).

It is worth mentioning that patients' responses while recalling the short descriptions, especially in the delayed recall trials, included several confabulation (i.e., production of statements that are incongruous to the present context; Dalla Barba, 1993) and prior-description intrusion (i.e., production of other story components that deviate from the to-be-remembered story; Dalla Barba et al., 2002) errors. These observations further confirm that the early stages of AD are characterised not only by substantial difficulty in retrieving newly-encoded information but also significant qualitative memory distortions. Past investigations have reported that AD patients often confabulate when required to retrieve episodic material (Dalla Barba, Nedjam, & Dubois, 1999), which has been considered to reflect a more or less intentional strategy to overcome memory lapses or a lack of supervisory control of the retrieval process (Burgess & Shallice, 1996; Desgranges et al., 2002; Moscovitch, 1995) and poor temporal awareness (Dalla Barba et al., 2002; Dalla Barba et al., 1999; Dalla Barba & Boissé, 2010; La Corte et al., 2010).

7.4.2 Naming

In the present study, a group of mild AD patients was significantly impaired in picture confrontation naming tasks in comparison to age-, education-, and gender- matched controls.

These results confirm previous studies that report naming deficits in patients at an early stage of AD (Faust et al., 2004; Balthazar et al., 2008; Lin et al., 2014), reflecting partial disintegration of semantic knowledge and poorer access-retrieval operations of lexical-semantic information, associated with anterior temporal lobe and prefrontal cortex damage (Adlam et al., 2006; Brambati et al., 2006; Joubert et al., 2010; Rogers & Friedman, 2008).

Beyond this overall lexical-semantic deficit, the primary goal was to investigate whether naming deficits in early AD are category specific. To that end, we examined three different categories, represented by different word classes: objects (nouns; BNT), actions (verbs, ANT), and spatial relations (spatial prepositions; SNT). From a theoretical standpoint, these results can help us develop hypotheses about 1) how the internal representations of semantic knowledge are organized, and 2) the nature of internal representations of space. Regarding the first issue, if the naming deficits were comparable across distinct semantic categories, then that would imply a cross-category lexical-semantic processing impairment, reflecting a general cognitive system for semantic representations. By contrast, we found that naming deficits in mild AD varied as a function of the category involved, with greater impairments in naming spatial relations compared to object and action naming deficits, and also, greater object than action naming declines. Naming involves three main processing stages, including perceptual encoding of the stimuli, access and retrieval of the corresponding semantic representation in the long-term memory, and production of the corresponding phonological output (Edwards et al., 2010). Encoding and identifying relational information, rather than identifying a single entity, is likely to pose higher demands on visuoperceptual operations. Moreover, generating appropriate terms to describe spatial relations requires additional transformation operations from perceptual to linguistic representations. Therefore, the main stages of naming for these distinct categories may be different in terms of processing demands. Ultimately, these findings suggest that the semantic representations for objects, actions, and spatial relations are, at least to some extent, supported by different neural circuits, as they are differentially affected by AD.

It can be therefore argued that the observed discrepancies on naming performance for objects, actions, and spatial relations reflect diverse extents of damage in their corresponding neural underpinning during the early stages of AD. Similar fronto-temporal networks are known to support both object and action naming, as demonstrated in lesion (e.g., Lu et al., 2002) and neuroimaging (e.g., Garn et al., 2009; Hernandez et al., 2001; Saccuman et al., 2006; Tyler et al., 2001) studies. However, both neuroimaging (e.g., Amorapanth et al., 2010; Damasio et al., 2001) and lesion (e.g., Göksun et al., 2013; Kemmerer & Tranel, 2003; Tranel

& Kemmerer, 2004; Wu et al., 2007) studies have previously shown that, apart from frontal and inferotemporal regions, the retrieval of spatial prepositions during confrontation picture naming tasks is additionally supported by parietal regions. The earliest and most intense histopathological changes in AD are initially found in the medial temporal lobes and parietal lobes, while extensive loss of neurons in inferior temporal and prefrontal areas occurs later (Harper et al., 2017; Shi et al., 2009). This could be the reason why object and action naming were found to be relatively better preserved than spatial naming in the present study. Moreover, it has been previously shown that AD patients display impairments on reasoning measures that require relational integration (Waltz et al., 2004).

Furthermore, we found relatively more severe object than action naming impairments in patients with mild AD. This finding is consistent with previous studies reporting a greater deficit for object compared to action naming in AD patients (e.g., Fung et al., 2001; Robinson et al., 1999; Williamson et al., 1998). Lesion studies have indicated that frontal damage in the left hemisphere predominantly affects action naming while damage in the inferior temporal lobe largely results in object naming deficits (e.g., Daniele et al., 1994; Shapiro & Caramazza, 2003; Tranel et al., 2001). Consequently, one possible explanation for this object-action naming discrepancy observed in our patient group is that verbs are supported predominantly by frontal brain structures that may be better preserved in early AD, while object naming relies more on temporal structures that are significantly affected by AD. In line with this assumption, repetitive transcranial magnetic stimulation to the dorsolateral prefrontal cortex may improve action but not object naming accuracy in early-stage AD patients (Cotelli et al., 2006, 2008). However, other reports suggest the opposite (e.g., Cappa et al., 1998; Druks et al., 2006), with action naming being less accurate and slower than object naming among patients with AD as well as healthy older adults (e.g., Masterson et al., 2007). The latter observation has been interpreted as verbs being semantically more complex than nouns and thus placing more demands on verbal processing operations (cf. Matzig, Druks, Masterson, & Vigliocco, 2009). The discrepancy between the present results and the evidence from these studies could be attributed to differential staging of dementia severity. After the initial disproportionate temporo-parietal atrophy, the ongoing neuropathological changes spread to frontal regions during the moderate stages of the disease (Frisoni et al., 2010; Harper et al., 2017; Jack et al., 2013).

Importantly, the present findings can also help us better understand the nature of the internal representations of space. The divergent decline in spatial language production observed in our patient group, whilst their verbal production for objects and actions was less affected, can be regarded as comparable to the well-documented impairments in visuospatial cognition characterizing the early stages of AD (Cushman et al., 2008; Tu et al., 2015, 2017; Yew et al., 2016). These results further confirm that linguistic and perceptual representations of space are supported by overlapping neural networks (Chatterjee, 2001; Noordzij et al., 2008), and argue in favour of a supramodal system supporting spatial knowledge, in which spatial representations are flexibly used within the verbal and perceptual domains (Struiksma et al., 2009; Struiksma & Postma, 2017). It is worth noting that our group of AD patients displayed a tendency to provide responses with spatial demonstratives (i.e., *here*, *there*) along with spatial deixis while completing the spatial naming task. It has also been observed that spatial deictic use during on-line route descriptions is increased among AD patients (March, Pattison, & Wales, 2009; March, Wales, & Pattison, 2006), possibly reflecting a compensation strategy to convey spatial information during discourse.

To conclude, the present data revealed differential category-dependent effects on naming deficits in mild AD, with far larger deficits in naming spatial relations compared to objects and actions, and poorer object than action naming accuracy. Notably, the SNT distinguished more accurately the two groups, resulting in higher sensitivity and specificity values than the BNT and ANT, which establishes its higher discriminative validity and diagnostic value in detecting mild AD. Future longitudinal studies should examine spatial naming amongst individuals at risk of developing AD (e.g., individuals with APOE ε4 genotype; Michaelson, 2014) in order to further explore SNT's sensitivity during preclinical stages of AD. Moreover, future research involving patients with different neurodegenerative conditions could establish whether the SNT could efficiently discriminate different dementias and therefore assist in early stage differential diagnosis of dementias.

7.4.3 Verbal comprehension under different spatial reference frames

People share information about where different objects are located in the natural environment almost on a daily basis. Apprehending verbally encoded locative information is therefore a crucial skill for numerous daily activities and in various social contexts. As previously discussed (see Section 2.2), mental representations of space can be communicated under different reference frames and perspectives, including self-centred, other-person-centred, object-centred, and environment-centred frames. The present study employed a novel task (VCSRF; see Section 3.2.4) to examine verbal comprehension of locative relations between two objects under these distinct spatial reference frames in patients at an early stage of AD.

Overall, mild AD patients were significantly less accurate in judging descriptions of spatial relations between two objects placed in the natural environment, compared to matched controls. This deficit was demonstrated across all reference frames considered. Notably, patients performed well above chance levels within a self-centred (about 82% correct) and an object-centred (75% correct) perspective, while their performance was just above chance level from a third-person-centred perspective (62%) and below chance level in the environment-centred frame (40%), whilst controls performed above chance level across all reference frames (see again Figure 29). The theoretical implications of the present findings extend to how spatial relations are mentally represented from different perspectives based on verbal inputs. The fact that patients' performance varied as a function of the reference frame employed indicates that at least partially distinct operations are involved in mentally representing space under different frames. By extent, these distinct cognitive operations must be supported by at least partially dissociable neural networks that are differentially affected by the AD pathological processes.

Adopting a third-person-perspective to frame spatial relations from verbal cues elicited the largest differences between mild AD patients and controls. Neuroimaging studies with healthy young adults have shown that posterior parietal regions, and specifically the precuneus, is involved in visuospatial imagery and third-person perspective transformations during mental viewpoint rotations (David et al., 2006; Lambrey, Doeller, Berthoz, & Burgess, 2012; for a review see Cavanna & Trimble, 2006). Moreover, increased activity in the precuneus has also been reported in processing sentences with a concrete spatial meaning (Wallentin et al., 2005) and in verbally-cued recalling of spatial relations (Wallentin, Roepstorff, Glove, & Burgess, 2006; Wallentin, Weed, Ostergaard, Mouridsen, & Roepstorff, 2008) in healthy young adults. Meanwhile, subtle changes in functional precuneus activity during visual encoding have been reported in preclinical stages of AD (Rami et al., 2012) while patients at an early stage of AD also exhibit significant reduction in precuneal volume (Ryu et al., 2010; Stricker et al., 2012). Although spatial third-person perspective taking has not been directly examined in AD patients, several studies have reported diminished social third-person perspective taking and theory of mind abilities (Ramanan et al., 2017), especially in the later disease stages (for a meta-analysis see Bora, Walterfang, & Velakoulis, 2015). Neuroimaging evidence has shown that mild AD patients recruit prefrontal regions but not visual associative areas when taking a third-person perspective for social judgements, suggesting that they rely more on reasoning processes than on visual imagery strategies (Ruby et al., 2009).

The finding of severely impaired performance under an environment-centred spatial reference frame is consistent with the large literature reporting poor allocentric spatial processing in mild AD. Importantly, our findings extend this literature by showing that this system is also diminished when accessed through language. It is well documented that AD patients experience significant difficulties in forming both egocentric (self-centred) and allocentric (environment-centred) representations of space. This has been evidenced in numerous AD studies employing virtual reality tasks for spatial orientation, wayfinding and route learning and memory and has been repeatedly attributed to hippocampal damage (e.g., Morganti, Stefanini, & Riva, 2013; Serino, Morganti, Di Stefano, & Riva, 2015; Tu et al., 2015, 2017; Yew et al., 2013; for a review see Serino et al., 2014). Patients with mild AD also show altered functional responses in brain regions associated with encoding of visual scenes, including medial temporal lobe and fusiform regions, although no such activation abnormalities are observed in occipital areas, reflecting a progressive activation deficit from primary through higher order areas of the ventral visual pathway (Golby et al., 2005). Along with hippocampal regions, the retrosplenial cortex with its strong connections to temporal, parietal, occipital, and frontal regions seems to play a key role in integrating and transforming visuospatial information within different reference frames (Vann, Aggleton, & Maguire, 2009) and has been associated with poor orientation in AD patients (Tu et al., 2017).

Patients were significantly less accurate in processing descriptions of spatial relations from an object-centred reference frame compared to a group of matched controls. However, this group discrepancy was substantially milder compared to the group differences observed in the other non-self-centred reference frames, i.e., the third-person- and environment-centred frames. This finding may be explained by the quantitative and qualitative differences in the mental integration and transformation operations required in these distinct frames. The reference object also defined the reference frame in the object-centred condition, thus putting less processing demands on the relevant cognitive resources. Moreover, the reference object used in this frame was a car model, which holds rich situation knowledge. Therefore, object-knowledge effects might have influenced the processing of spatial relations (cf. Coventry & Garrod, 2004, 2005) by triggering implicit simulations of self-based mental rotations (Kessler & Rutherford, 2010; Kessler & Thomson, 2010; Michelon & Zacks, 2006).

To conclude, using the novel VCSRF task we demonstrated significant impairments in verbal processing of spatial relational information under different spatial reference references in mild AD. The VCSRF, especially in the third-person-centred perspective, produced excellent specificity and sensitivity values establishing its diagnostic validity in accurately discriminating early AD patients from age-, education-, and gender-matched controls.

7.5 Conclusions

This series of studies constituted a first attempt to systematically investigate different aspects of spatial language processing, including production, memory, and comprehension, in patients at an early stage of AD. The findings extend the large existing literature reporting significant impairments in various spatial abilities in early AD by demonstrating for the first time that spatial processing is also compromised when assessed through language. Crucially, these further support the hypothesis of a supramodal cognitive system that enables flexible representations of space within the verbal and perceptual domain.

Apart from the aforementioned theoretical contributions, the present findings have direct clinical implications as they offer fresh insights into AD patients' mental functioning during the early stages of the disease, and enrich our knowledge of their cognitive profile with regards to generating, apprehending, and remembering spatial information from verbal descriptions. As we established the novel spatial language tests' discriminative validity, an interesting avenue for future work will be to assess these functions in individuals at risk of developing AD, as well as across different clinical populations with cognitive impairments. The use of spatial language measures in conjunction with other cognitive markers can enhance the sensitivity and specificity of AD diagnosis.

Chapter 8 General discussion

8.1 Synopsis and implications

Space epitomises one of the core framing structures of experience in the natural world. Spatial representations may derive from diverse sources, ranging from direct visual and navigational grounded experience to the use of symbolic linguistic constructs, such as spatial descriptions.

Our ability to use words to refer to spatial relations is vital for managing numerous everyday activities and constitutes a major and distinct part of human linguistic communication. Although people can generate, apprehend, and remember spatial descriptions quite efficiently and effortlessly even within different spatial reference frames, these processes entail demanding operations of transformation of information between perceptual representations and linguistic formats.

The present project primarily aimed to address how different aspects of spatial language processing may change across the adult-lifespan and in mild Alzheimer's disease (AD). To that end, we first developed some novel tests for the assessment of spatial-verbal production, memory, and comprehension. Based on earlier neuropsychological work, we developed the Spatial Naming Test, requiring naming static and dynamic spatial relations between objects, as an analogue of existing picture-confrontation naming tests for objects (Boston Naming Test; Kaplan et al., 2001) and actions (Action Naming Test; Obler & Albert, 1979). The Spatial Verbal Memory task was developed as an analogue of the Logical Memory subscale of the WMS (Wechsler, 2010), and involved immediate and delayed recall trials of spatial descriptions presented from a person-centred route perspective or from a landmark-centred survey perspective. Finally, the task developed for spatial-verbal comprehension involved judging descriptions of spatial relational information between objects under four distinct spatial reference frames: a self-centred, a third-person-centred, an object-centred, and an environment-centred reference frame (Verbal Comprehension in Spatial Reference Frames). Using a sample of healthy young adults, we established the test-retest reliability of the novel measures.

Next, a large cohort of healthy adults, ranging in age from 18 to 85 years, were administered the novel spatial language tasks along with a comprehensive battery of well-established tests assessing various core and higher order cognitive processes across the verbal and visuospatial domains. The results of this series of studies revealed striking evidence for a number of general points about ageing and cognition. First, overall, different cognitive functions start to change at different timepoints over the adult-lifespan, at different rates, and at different extents. Second, ageing effects on core processing resources are largely domain-specific: Processing speed and short-term and working memory capacity for visual and spatial information deteriorate with increasing age, while, by contrast, processing resources for verbal information remain relatively resilient to ageing effects. Third, ageing effects on higher-order cognitive abilities are also domain-specific: On the one hand, different aspects of lexical-semantic abilities, including naming objects and actions, and vocabulary knowledge, show small increases or remain well preserved across the adult-lifespan. On the other hand, there are age-related declines across various aspects of visuospatial abilities, such as visuospatial organization, reasoning, object-based mental rotation, and object-perspective taking, although their onset and magnitude depend on the type of spatial subability examined. Fourth, short-term episodic memory capacity decreases in late adulthood regardless the content domain, but the changes in long-term episodic memory are domain-specific, with substantial deterioration for visuospatial information against mild changes for verbal information.

These results offer a more complete understanding of the typical ageing effects on cognitive functioning, and demonstrate differential domain-specific changes with increasing age. However, the most important findings of these studies concern the adult-lifespan trajectories of spatial-verbal abilities. In keeping with the starting hypothesis, over a series of studies on spatial-verbal production, memory, and comprehension, results revealed that age-related changes in spatial language abilities are comparable to those observed across visuospatial abilities and in contrast to analogous (non-spatial) verbal abilities. While naming accuracy for static and dynamic spatial relations declines with increasing age, naming accuracy for objects and actions remains intact across the lifespan. Similarly, there are age-related impairments in the long-term memory capacity for spatial descriptions, presented either from a route or a survey perspective, whereas the ability to maintain verbal information is far less affected as one ages. Moreover, processing spatial descriptions about locative information from a third-person perspective or from an environment-centred spatial reference frame is significantly impaired in late adulthood.

Finally, the last series of studies demonstrated that patients at an early stage of AD exhibit significant impairments in spatial language abilities, including production, memory, and comprehension of spatial descriptions, when compared to age-, education-, and gender-matched controls. These findings extend the large existing literature reporting severe declines in various spatial abilities in early AD by demonstrating that spatial processing is also compromised when assessed through language. Notably, all spatial language measures showed high levels of diagnostic sensitivity, and the SNT could better discriminate healthy from pathological ageing than analogous (non-spatial) verbal measures. These findings have clear diagnostic implications in that clinicians should consider employing spatial language measures to identify and discriminate neurodegenerative conditions.

Taken together, the main findings outlined above suggest that individuals who experience difficulties in perception-based visuospatial operations also exhibit impairments in language-based visuospatial operations, despite their less affected language abilities. This pattern was observed consistently across different measures of cognitive functions (production, comprehension, and long-term memory) and across different populations (older adults and patients with mild AD). Thus, the observed patterns imply that linguistic and non-linguistic representations of space are underpinned by comparable cognitive operations supported by overlapping neural networks that are particularly sensitive to (a)typical ageing effects. Consequently, they align well with the idea that a supramodal cognitive system is necessary to support spatial representations arising from different sources, as previously suggested by Postma and colleagues (Struiksma et al., 2009; Struiksma & Postma, 2017). They are also in accordance with reports of a close connection between linguistic and non-linguistic representations of space, as illustrated across developmental (e.g., Nys et al., 2014), behavioural (e.g., Coventry et al., 2014; Hayward & Tarr, 1995), cross-linguistic (e.g., Munnich et al., 2001), and neuroimaging (e.g., Noordzij et al., 2008; Wallentin et al., 2005, 2008) studies. Nevertheless, the present results should be corroborated by future investigations employing both cross-sectional and longitudinal designs.

Another significant contribution of the present project with potentially widespread practical implications is the development and validation of novel tests for the reliable assessment of different spatial language abilities, including spatial-verbal production, comprehension, and memory. Across a series of studies, we established the tests' test-retest reliability, concurrent and construct validity, as well as their discriminant validity for mild AD patients. We also determined the influence of demographic factors, and in particular the effects of age, education, and gender on performance on each test, and subsequently produced demographically-adjusted normative data for the British population. These brief and simple tests can provide reliable and valid means of spatial language assessments in future experimental and clinical investigations on human cognition.

8.2 Future directions

The current work resulted in a number of new insights regarding spatial language abilities in typical and atypical ageing populations, with several theoretical and practical implications that have been discussed in detail in the previous chapters and outlined above. It also opens a number of interesting avenues for future research that are presented below.

8.2.1 (A)typically developing populations

Rather than comparing two age groups representing the extremes of the adult-lifespan (i.e., younger and older adults), the ageing studies presented in this thesis (Chapter 5) employed a cross-sectional design and followed a carefully considered protocol of participant selection to cover a broad age range and achieve optimum age distributions for each age group considered. Nevertheless, additional investigations that adopt similar cross-sectional as well as longitudinal designs are required in order to replicate the present findings, and thus draw stronger conclusions. A limitation of the present studies was that no individuals in their 30s were included in the adult-lifespan sample. This was a result of practical difficulties in recruiting adults aged between 30-44, who seem less eager to participate in long testing sessions, most likely due to demanding daily schedules. Age-related differences in spatial cognition typically start to emerge during or even after middle age (i.e., between 45-65), and, therefore, group differences between younger adults in their 20s and 30s were not anticipated, however, future research should examine whether there are any changes in spatial language abilities occurring at that timepoint of the lifespan.

Past research has identified a number of age-associated changes in the neural underpinning of diverse spatial abilities (see Section 4.2.3), however, there is considerable lack of research examining spatial language abilities in ageing from a neural standpoint. Therefore, it would be particularly interesting for future research to investigate age-related structural and functional changes associated with spatial language abilities and identify whether there are significant age differences in the neural networks engaged while generating, encoding, processing, and recalling spatial descriptions within different spatial reference frames.

The second series of studies focused on the adult-lifespan trajectories of spatial language, (non-spatial) verbal, and (non-verbal) visuospatial abilities. Although there is a rich literature on the acquisition of spatial semantics early in development (see Section 2.3), this research has often focused on a limited range of spatial concepts at a time, such as containment or support, or spatial orientation. Thus, an interesting avenue for future work would be to employ the newly developed spatial language measures presented here to identify the developmental trajectories of diverse aspects of spatial language abilities and contrast them against the developmental trajectories of analogous non-spatial verbal and non-verbal visuospatial abilities early in life.

The third series of studies in the current project (Chapter 7) focused on spatial language impairments amongst patients at an early stage of AD. It is important that the findings of these studies are corroborated in larger samples of mild AD patients. A promising avenue for future studies would be to examine whether performance in the newly developed spatial language measures could discriminate individuals at risk of developing AD, for example, due to familiar history or presence of APOE ε4 genotype or mild cognitive impairment, and matched controls. Longitudinal follow-up examinations of spatial language abilities along with their structural and functional neural correlates could help established pathologically induced changes across various stages of preclinical and clinical progression in AD.

Reliable cognitive markers are required not only for (a) detecting at risk individuals prior to disease onset and (b) accurately diagnosing and staging disease progression (Snyder et al., 2014), but also for (c) assisting and improving the differential diagnosis of patient groups that present similar memory impairments. Past studies have shown that patients at the early stages of AD and frontotemporal dementia (FTD) may exhibit comparable amnesic symptoms (Hornberger et al., 2010), which may lead to diagnostic uncertainty. Recent evidence, however, suggests that spatial disorientation is impaired in AD, but relatively intact in FTD patients (Hornberger et al., 2010; Tu et al., 2015, 2017). Thus, an interesting proposal for future investigations would be to examine whether the spatial language tasks can be used not only to reliably detect pathological ageing, but also to discriminate between patients with different neurodegenerative conditions, such as AD and FTD, beyond their memory impairments. As well as improving diagnosis, clinical practitioners and future dementia studies should utilize and take into account the present findings when outlining therapeutic targets, on the one hand, and developing corresponding intervention designs, on the other.

The novel spatial language measures could also be employed in future work on neurodevelopmental conditions. Examining a broad spectrum of spatial language abilities in children with developmental language impairments on the one hand and conditions characterized by visuospatial impairments (e.g., William’s syndrome) on the other hand, can provide fresh insights on the relative contribution of linguistic and non-linguistic skills on spatial semantics. Another suggestion for future investigations would be to investigate the mapping between spatial cognition and spatial language abilities in individuals with autistic spectrum disorder. For example, certain aspects of visuospatial processing appear to be intact in high-functioning individuals with autism in the face of poor language abilities (e.g., Edgin & Pennington, 2005; Sahyoun et al., 2010), but their ability to generate, process, and remember spatial descriptions is largely unexplored. Moreover, while several studies have reported difficulties in third-person visual perspective taking in children with autism (e.g., Hamilton, Brindley, & Frith, 2009), it remains open whether they experience similar difficulties when exposed to spatial descriptions (rather than visual stimuli) within different perspectives and spatial reference frames, both in the presence and absence of other social agents.

A different and ambitious line of research for future investigations would be to explore whether the linguistic environment can substantially influence the mapping between spatial language and spatial abilities across both typically and atypically developing populations. This could be explored in cross-linguistic paradigms, as well as in bilingual populations.

8.2.2 Categorical versus coordinate spatial information

The novel measures used in the present studies were designed to focus on categorical spatial information. Categorical representations capture arbitrary and gross properties of spatial relations that can be defined by prepositional terms, whereas coordinate representations involve precise metric information, such as distances between objects (Kosslyn, 1987). It has been suggested that categorical and coordinate spatial processing is underpinned by distinct neural substrates, with the right hemisphere being crucial in coordinate representations, while categorical representations are more left lateralized (e.g., Baumann, Chan, & Mattingley, 2012; van der Ham, Raemaekers, van Wezel, Oleksiak, & Postma, 2009; for a review, see Jager & Postma, 2003). Moreover, it has been revealed that the hippocampal formation is crucial for encoding coordinate spatial information while categorical spatial relations are supported by parietal regions (e.g., Baumann et al., 2012; for a review, see Baumann & Mattingley, 2014). Although a few existing studies have failed to find differential ageing effects for categorical versus coordinate spatial computations (e.g., Meadmore, Dror, & Bucks, 2009), even during verbal multiple-choice tasks (e.g., Bruyer, Scailquin, & Coibion, 1997), more investigations are required to examine the mapping between spatial language production, comprehension, and memory and non-verbal visuospatial abilities for both categorical and coordinate spatial information, from an (a)typical developmental and ageing perspective.

8.2.3 Geometrical versus extra-geometrical features

As previously discussed, the spatial language measures used in the present studies were developed to tap geometry-defined locativel relations. For example, the Spatial Naming Test included abstract geometrical objects rather than everyday concrete objects, in order to avoid object-knowledge effects or biased responses based on overlearned descriptions of commonly encountered spatial relations (e.g., “the cat is *on* the mat”), or merely language-specific conventionalized descriptions of spatial relations (e.g., “the bird is *in* the tree” or “the fly is *on* the ceiling”, or the difference between “being *in* the car” versus “being *on* the bus”, or “the food *in* the dish” versus “the food *on* the plate”). However, as previously discussed (see section 2.1) it is well documented that *what* objects are and *how* they typically relate to other objects can influence spatial preposition selection (Coventry et al., 2001, 2010, 2014; see also Coventry & Garrod, 2004). Therefore, it would be of great interest for future studies to investigate the possibility of differential age effects on spatial language abilities for geometry-defined spatial relations versus spatial relations that are co-defined by extra-geometric features (for example spatial relations between concrete objects with rich situational knowledge). Conceptual and semantic knowledge, as well as word-to-word associations and language-specific conventionalized descriptions slowly build up over the course of the lifetime and are typically well-maintained in old age. Thus, one might expect that spatial language abilities for relations that are co-defined by extra-geometric factors, such as prior object knowledge or knowledge of word-to-word associations, would be preserved in ageing, in contrast to the age-related declines in spatial language abilities for geometry-based relations described in the present work. By extension, one might expect relatively poor spatial language abilities for the former relations early in development.

These hypotheses could also be considered in studies with first- and second-language speakers. It is assumed that first-language speakers would perform equally well on spatial language measures for both types of spatial relations, whereas the performance of second-language speakers would be comparable to that of first-language speakers on spatial language measures for geometry-based relations, but poorer for spatial relations that are also defined by extra-geometric factors due to potentially poorer word-to-word associations.

8.3 Concluding remarks

The results of the present project provided fresh knowledge about the cognitive changes that occur in typical and atypical ageing and have several practical and theoretical implications. From a practical standpoint, one of the most important contributions of the present work is the development of reliable and valid measures of spatial language abilities that are quick and easy to administer even to vulnerable populations. Moreover, the present work lead to the identification of novel cognitive markers of typical and atypical ageing that could be used in clinical settings for earlier and more accurate diagnosis and staging of neurodegenerative conditions. From a theoretical standpoint, the current findings align well with the idea that a supramodal cognitive system is necessary to support spatial representations arising from different sources. Finally, the novel findings presented in this project open a number of exciting avenues for future research.

References

Abbott, A. (2011). Dementia: A problem for our age. *Nature*, *475*(7355), S2-S4.

Abe, M., Suzuki, K., Okada, K., Miura, R., Fuji, T., Etsurou, M., & Yamadori, A. (2004). Normative data on tests for frontal lobe functions: Trail Making Test, Verbal fluency, Wisconsin Card Sorting Test. *Brain and Nerve*, *56*(7), 567-574.

Adamo, D. E., Briceño, E. M., Sindone, J. A., Alexander, N. B., Moffat, S. D., & May, M. (2012). Age differences in virtual environment and real world path integration. *Frontiers in Aging Neuroscience, 4*: 25.

Adlam, A. L. R., Bozeat, S., Arnold, R., Watson, P., & Hodges, J. R. (2006). Semantic knowledge in mild cognitive impairment and mild Alzheimer's disease. *Cortex*, *42*(5), 675-684.

Akers, K. G., & Hamilton, D. A. (2007). Comparison of developmental trajectories for place and cued navigation in the Morris water task. *Developmental Psychobiology, 49*(6), 553-564.

Albert, M. S., DeKosky, S. T., Dickson, D., Dubois, B., Feldman, H. H., Fox, N. C., Gamst, A., Holtzman, D. M., Jagust, W. J., Petersen, R. C., & Snyder, P. J. (2011). The diagnosis of mild cognitive impairment due to Alzheimer’s disease: Recommendations from the National Institute on Aging-Alzheimer’s Association workgroups on diagnostic guidelines for Alzheimer's disease. *Alzheimer's & Dementia*, *7*(3), 270-279.

Albert, M. S., Moss, M. B., Tanzi, R., & Jones, K. (2001). Preclinical prediction of AD using neuropsychological tests. *Journal of the International Neuropsychological Society, 7*(5), 631-639.

Albinet, C. T., Boucard, G., Bouquet, C. A., & Audiffren, M. (2012). Processing speed and executive functions in cognitive aging: How to disentangle their mutual relationship? *Brain and Cognition*, *79*(1), 1-11.

Alegret, M., Boada-Rovira, M., Vinyes-Junqué, G., Valero, S., Espinosa, A., Hernández, I., & Tárraga, L. (2009). Detection of visuoperceptual deficits in preclinical and mild Alzheimer's disease. *Journal of Clinical and Experimental Neuropsychology*, *31*(7), 860-867.

Alichniewicz, K. K., Brunner, F., Klünemann, H. H., & Greenlee, M. W. (2012). Structural and functional neural correlates of visuospatial information processing in normal aging and amnestic mild cognitive impairment. *Neurobiology of Aging*, *33*(12), 2782-2797.

Alzheimer's Association. (2016). 2016 Alzheimer's disease facts and figures. *Alzheimer's & Dementia*, *12*(4), 459-509.

Amodio, P., Wenin, H., Del Piccolo, F., Mapelli, D., Montagnese, S., Pellegrini, A., Musto, C., Gatta, A., & Umiltà, C. (2002). Variability of trail making test, symbol digit test and line trait test in normal people. A normative study taking into account age-dependent decline and sociobiological variables. *Aging Clinical and Experimental Research*, *14*(2), 117-131.

Amorapanth, P., Kranjec, A., Bromberger, B., Lehet, M., Widick, P., Woods, A. J., Kimberg, D. Y., & Chatterjee, A. (2012). Language, perception, and the schematic representation of spatial relations. *Brain and Language*, *120*(3), 226-236.

Amorapanth, P. X., Widick, P., & Chatterjee, A. (2010). The neural basis for spatial relations. *Journal of Cognitive Neuroscience*, *22*(8), 1739-1753.

Ankowski, A. A., Thom, E. E., Sandhofer, C. M., & Blaisdell, A. P. (2012). Spatial language and children’s spatial landmark use. *Child Development Research, 2012*, 1-14.

Antonova, E., Parslow, D., Brammer, M., Dawson, G. R., Jackson, S. H. D., & Morris, R. G. (2009). Age-related neural activity during allocentric spatial memory. *Memory*, *17*(2), 125-143.

Apostolova, L. G., Green, A. E., Babakchanian, S., Hwang, K. S., Chou, Y. Y., Toga, A. W., & Thompson, P. M. (2012). Hippocampal atrophy and ventricular enlargement in normal aging, mild cognitive impairment and Alzheimer's disease. *Alzheimer Disease and Associated Disorders, 26*(1), 17.

Apostolova, L. G., Lu, P., Rogers, S., Dutton, R. a, Hayashi, K. M., Toga, A. W., Cummings, J. L., et al. (2008). 3D mapping of language networks in clinical and pre-clinical Alzheimer's disease. *Brain and Language*, *104*(1), 33-41.

Arévalo, A., Perani, D., Cappa, S. F., Butler, A., Bates, E., & Dronkers, N. (2007). Action and object processing in aphasia: From nouns and verbs to the effect of manipulability. *Brain and Language*, *100*(1), 79-94.

Aronoff, J. M., Gonnerman, L. M., Almor, A., Arunachalam, S., Kempler, D., & Andersen, E. S. (2006). Information content versus relational knowledge: Semantic deficits in patients with Alzheimer's disease. *Neuropsychologia*, *44*(1), 21-35.

Arvanitakis, Z., Capuano, A. W., Leurgans, S. E., Bennett, D. A., & Schneider, J. A. (2016). Relation of cerebral vessel disease to Alzheimer's disease dementia and cognitive function in elderly people: A cross-sectional study. *The Lancet Neurology*, *15*(9), 934-943.

Attali, E., De Anna, F., Dubois, B., & Barba, G. D. (2008). Confabulation in Alzheimer's disease: Poor encoding and retrieval of over-learned information. *Brain*, *132*(1), 204-212.

Bäckman, L., Jones, S., Berger, A. K., Laukka, E. J., & Small, B. J. (2005). Cognitive impairment in preclinical Alzheimer's disease: A meta-analysis. *Neuropsychology*, *19*(4), 520-531.

Bäckman, L., Small, B. J., & Fratiglioni, L. (2001). Stability of the preclinical episodic memory deficit in Alzheimer's disease. *Brain*, *124*(1), 96-102.

Balcomb, F., Newcombe, N. S., & Ferrara, K. (2011). Finding where and saying where: Developmental relationships between place learning and language in the first year. *Journal of Cognition and Development*, *12*(3), 315-331.

Baldo, J. V., Schwartz, S., Wilkins, D., & Dronkers, N. F. (2006). Role of frontal versus temporal cortex in verbal fluency as revealed by voxel-based lesion symptom mapping. *Journal of the International Neuropsychological Society*, *12*(6), 896-900.

Balthazar, M. L. F., Cendes, F., & Damasceno, B. P. (2008). Semantic error patterns on the Boston Naming Test in normal aging, amnestic mild cognitive impairment, and mild Alzheimer's disease: is there semantic disruption? *Neuropsychology*, *22*(6), 703.

Band, G. P., & Kok, A. (2000). Age effects on response monitoring in a mental-rotation task. *Biological Psychology*, *51*(2), 201-221.

Barnard, N.D., Bush, A.I., Ceccarelli, A., Cooper, J., de Jager, C.A., Erickson, K.I., Fraser, G., Kesler, S., Levin, S.M., Lucey, B. and Morris, M.C. (2014). Dietary and lifestyle guidelines for the prevention of Alzheimer's disease. *Neurobiology of Aging*, *35*, S74-S78.

Barresi, B. A., Nicholas, M., Tabor Connor, L., Obler, L. K., & Albert, M. L. (2000). Semantic degradation and lexical access in age-related naming failures. *Aging, Neuropsychology, and Cognition*, *7*(3), 169-178.

Baumann, O., Chan, E., & Mattingley, J. B. (2012). Distinct neural networks underlie encoding of categorical versus coordinate spatial relations during active navigation. *Neuroimage*, *60*(3), 1630-1637.

Baumann, O., & Mattingley, J. B. (2014). Dissociable roles of the hippocampus and parietal cortex in processing of coordinate and categorical spatial information. *Frontiers in Human Neuroscience*, *8*: 73.

Begega, A., Cienfuegos, S., Rubio, S., Santín, J. L., Miranda, R., & Arias, J. L. (2001). Effects of ageing on allocentric and egocentric spatial strategies in the Wistar rat. *Behavioural Processes*, *53*(1-2), 75-85.

Béland, R., & Lecours, A. R. (1990). The MT-86 β aphasia battery: A subset of normative data in relation to age and level of school education. *Aphasiology*, *4*(5), 439-462.

Belmonti, V., Cioni, G., & Berthoz, A. (2015). Switching from reaching to navigation: Differential cognitive strategies for spatial memory in children and adults. *Developmental Science*, *18*(4), 569-586.

Benito-Cuadrado, M. M., Esteba-Castillo, S., Böhm, P., Cejudo-Bolivar, J., & Peña-Casanova, J. (2002). Semantic verbal fluency of animals: a normative and predictive study in a Spanish population. *Journal of Clinical and Experimental Neuropsychology*, *24*(8), 1117-1122.

Bennett, P. J., Sekuler, R., & Sekuler, A. B. (2007). The effects of aging on motion detection and direction identification. *Vision Research*, *47*(6), 799-809.

Berlingeri, M., Danelli, L., Bottini, G., Sberna, M., & Paulesu, E. (2013). Reassessing the HAROLD model: Is the hemispheric asymmetry reduction in older adults a special case of compensatory-related utilisation of neural circuits? *Experimental Brain Research, 224*(3), 393-410.

Bernard, J. A., & Seidler, R. D. (2012). Evidence for motor cortex dedifferentiation in older adults. *Neurobiology of Aging*, *33*(9), 1890-1899.

Bird, C. M., & Burgess, N. (2008). The hippocampus and memory: Insights form spatial processing. *Nature Reviews Neuroscience*, *9*(3), 182-194.

Birn, R. M., Kenworthy, L., Case, L., Caravella, R., Jones, T. B., Bandettini, P. A., & Martin, A. (2010). Neural systems supporting lexical search guided by letter and semantic category cues: a self-paced overt response fMRI study of verbal fluency. *NeuroImage*, *49*(1), 1099-1107.

Blair, M., Marczinski, C. A., Davis-Faroque, N., & Kertesz, A. (2007). A longitudinal study of language decline in Alzheimer's disease and frontotemporal dementia. *Journal of the International Neuropsychological Society*, *13*(2), 237-245.

Bo, J., Borza, V., & Seider, R. D. (2009). Age-related declines in visuospatial working memory correlate with deficits in explicit motor sequence learning. *Journal of Neurophysiology, 102*(5), 2744-2754.

Bohbot, V. D., Mckenzie, S., Konishi, K., Fouquet, C., Kurdi, V., Schachar, R., Boivin, M., & Robaey, P. (2012). Virtual navigation strategies from childhood to senescence: Evidence for changes across the life span. *Frontiers on Aging Neuroscience*, *4*: 28.

Bokde, A. L., Lopez-Bayo, P., Born, C., Ewers, M., Meindl, T., Teipel, S. J., Faltraco, F., Reiser, M. F., Möller, H. J., & Hampel, H. (2010). Alzheimer disease: Functional abnormalities in the dorsal visual pathway. *Radiology*, *254*(1), 219-226.

Bolla, K. I., Lindgren, K. N., Bonaccorsy, C., & Bleecker, M. L. (1990). Predictors of verbal fluency (FAS) in the healthy elderly. *Journal of Clinical Psychology*, *46*(5), 623-628.

Bondi, M. W., Jak, A. J., Delano-Wood, L., Jacobson, M. W., Delis, D. C., & Salmon, D. P. (2008). Neuropsychological contributions to the early identification of Alzheimer’s disease. *Neuropsychology Review*, *18*(1), 73-90.

Bopp, K. L., & Verhaeghen, P. (2005). Aging and verbal memory span: A meta-analysis. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, *60*(5), 223-233.

Bora, E., Walterfang, M., & Velakoulis, D. (2015). Theory of mind in behavioural-variant frontotemporal dementia and Alzheimer's disease: a meta-analysis. *Journal of Neurology, Neurosurgery and Psychiatry*, *86*(7), 714-719.

Borella, E., Meneghetti, C., Ronconi, L., & De Beni, R. (2014). Spatial abilities across the adult life span. *Developmental Psychology*, *50*(2), 384-392.

Borghesani, P. R., Madhyastha, T. M., Aylward, E. H., Reiter, M. A., Swarny, B. R., Schaie, K. W., & Willis, S. L. (2013). The association between higher order abilities, processing speed, and age are variably mediated by white matter integrity during typical aging. *Neuropsychologia*, *51*(8), 1435-1444.

Bowerman, M., & Choi, S. (2001). Shaping meanings for language: universal and language-specific in the acquisition of semantic categories. In *Language acquisition and conceptual development* (pp. 475-511). Cambridge University Press.

Bowerman, M., & Choi, S. (2003). Space under construction: Language-specific spatial categorization in first language acquisition. *Language in mind: Advances in the study of language and thought*, 387-427.

Brambati, S. M., Myers, D., Wilson, A., Rankin, K. P., Allison, S. C., Rosen, H. J., Miller, B. L., & Gorno-Tempini, M. L. (2006). The anatomy of category-specific object naming in neurodegenerative diseases. *Journal of Cognitive Neuroscience*, *18*(10), 1644-1653.

Brayne, C., Fox, C., & Boustani, M. (2007). Dementia screening in primary care: Is it time? *JAMA*, *298*(20), 2409-2411.

Brickman, A. M., Paul, R. H., Cohen, R. A., Williams, L. M., MacGregor, K. L., Jefferson, A. L., Tate, D. F., Gunstad, J., & Gordon, E. (2005). Category and letter verbal fluency across the adult lifespan: Relationship to EEG theta power. *Archives of Clinical Neuropsychology*, *20*(5), 561-573.

Brookmeyer, R., Johnson, E., Ziegler-Graham, K., & Arrighi, H. M. (2007). Forecasting the global burden of Alzheimer’s disease. *Alzheimer's & dementia*, *3*(3), 186-191.

Bruyer, R., Scailquin, J. C., & Coibion, P. (1997). Dissociation between categorical and coordinate spatial computations: Modulation by cerebral hemispheres, task properties, mode of response, and age. *Brain and Cognition*, *33*(3), 245-277.

Buckner, R. L., Sepulcre, J., Talukdar, T., Krienen, F. M., Liu, H., Hedden, T., & Johnson, K. A. (2009). Cortical hubs revealed by intrinsic functional connectivity: Mapping, assessment of stability, and relation to Alzheimer's disease. *Journal of Neuroscience, 29*(6), 1860-1873.

Buckner, R. L., Snyder, A. Z., Shannon, B. J., LaRossa, G., Sachs, R., Fotenos, A. F., & Mintun, M. A. (2005). Molecular, structural, and functional characterization of Alzheimer's disease: Evidence for a relationship between default activity, amyloid, and memory. *Journal of Neuroscience*, *25*(34), 7709-7717.

Bugg, J. M., DeLosh, E. L., Davalos, D. B., & Davis, H. P. (2007). Age differences in Stroop interference: contributions of general slowing and task-specific deficits. *Aging, Neuropsychology, and Cognition*, *14*(2), 155-167.

Bullens, J., Iglói, K., Berthoz, A., Postma, A., & Rondi-Reig, L. (2010). Developmental time course of the acquisition of sequential egocentric and allocentric navigation strategies. *Journal of Experimental Child Psychology*, *107*(3), 337-350.

Burgess, N. (2006). Spatial memory: How egocentric and allocentric combine. *Trends in Cognitive Sciences*, *10*(12), 551-557.

Burgess, N. (2008). Spatial cognition and the brain. *Annals of the New York Academy of Sciences*, *1124*(1), 77-97.

Burgess, N., Maguire, E. A., & O’Keefe, J. (2002). The human hippocampus and spatial and episodic memory. *Neuron*, *35*(4), 625-641.

Burgess, P. W., & Shallice, T. (1996). Bizarre responses, rule detection and frontal lobe lesions. *Cortex*, *32*(2), 241-259.

Burke, D. M., MacKay, D. G., Worthley, J. S., & Wade, E. (1991). On the tip of the tongue: What causes word finding failures in young and older adults? *Journal of Memory and Language, 30*(5), 542-579.

Cabeza, R. (2002). Hemispheric asymmetry reduction in older adults: the HAROLD model. *Psychology and Aging*, *17*(1), 85-100.

Cabeza, R., Anderson, N. D., Locantore, J. K., & McIntosh, A. R. (2002). Aging gracefully: Compensatory brain activity in high-performing older adults. *NeuroImage*, *17*(3), 1394-1402.

Cabeza, R., Daselaar, S. M., Dolcos, F., Prince, S. E., Budde, M., & Nyberg, L. (2004). Task-independent and task-specific age effects on brain activity during working memory, visual attention and episodic retrieval. *Cerebral Cortex*, *14*(4), 364-375.

Caccappolo-Van Vliet, E., Manly, J., Tang, M. X., Marder, K., Bell, K., & Stern, Y. (2003). The neuropsychological profiles of mild Alzheimer's disease and questionable dementia as compared to age-related cognitive decline. *Journal of the International Neuropsychological Society*, *9*(5), 720-732.

Caffarra, P., Vezzadini, G., Dieci, F., Zonato, F., & Venneri, A. (2002). Rey-Osterrieth complex figure: Normative values in an Italian population sample. *Neurological Sciences*, *22*(6), 443-447.

Cappa, S. F., Binetti, G., Pezzini, A., Padovani, A., Rozzini, L., & Trabucchi, M. (1998). Object and action naming in Alzheimer's disease and frontotemporal dementia. *Neurology*, *50*(2), 351-355.
Cappell, K. A., Gmeindl, L., & Reuter-Lorenz, P. A. (2010). Age differences in prefrontal recruitment during verbal working memory maintenance depend on memory load. *Cortex, 46*(4), 462-473.
Carlesimo, G. A., Cherubini, A., Caltagirone, C., & Spalletta, G. (2010). Hippocampal mean diffusivity and memory in healthy elderly individuals: A cross-sectional study. *Neurology*, *74*(3), 194-200.
Carlson, L. A. (1999). Selecting a reference frame. *Spatial Cognition and Computation, 1*(4), 365-379.
Carlson-Radvansky, L. A., & Irwin, D. E. (1993). Frames of reference in vision and language: Where is above? *Cognition, 46*, 223-244.
Carlson-Radvansky, L. A., & Irwin, D. E. (1994). Reference frame activation during spatial term assignment. *Journal of Memory and Language*, *33*, 646-671.
Carlson-Radvansky, L. A., & Logan, G. D. (1997). The influence of reference frame selection on spatial template construction. *Journal of Memory and Language, 37*, 411-437.
Carlson-Radvansky, L. A., & Jian, Y. (1998). Inhibition accompanies reference frame selection. *Psychological Science, 7*, 56-60.
Carlson-Radvansky, L. A., & Radvansky, G. A. (1996). The influence of functional relations on spatial term selection. *Psychological Science, 7*, 56-60.
Carlson, L. A., & Van Deman, S. R. (2004). The space in spatial language. *Journal of Memory and Language*, *51*(3), 418-436.
Carlson, L. A., & Van Deman, S. (2008). Inhibition within a reference frame during the interpretation of spatial language. *Cognition*, *106*, 384-407.
Carstensen, L. L., Turan, B., Scheibe, S., Ram, N., Ersner-Hershfield, H., Samanez-Larkin, G. R., Brooks, K. P., & Nesselroade, J. R. (2011). Emotional experience improves with age: Evidence based on over 10 years of experience sampling. *Psychology and Aging*, *26*(1), 21-33.
Casasola, M. (2005). Can language do the driving? The effect of linguistic input on infants' categorization of support spatial relations. *Developmental Psychology, 41*(1), 183-192.
Casasola, M. (2008). The development of infants' spatial categories. *Current Directions in Psychological Science*, *17*(1), 21-25.
Cassel, J. C., Lazaris, A., Birthelmer, A., & Jackisch, R. (2007). Spatial reference-(not working-or procedural-) memory performance of aged rats in the water maze predicts the magnitude of sulpiride-induced facilitation of acetylcholine release by striatal slices. *Neurobiology of Aging*, *28*(8), 1270-1285.
Catricalà, E., Della Rosa, P. A., Plebani, V., Perani, D., Garrard, P., & Cappa, S. F. (2015). Semantic feature degradation and naming performance. Evidence from neurodegenerative disorders. *Brain and Language, 147*, 58-65.
Cavaco, S., Gonçalves, A., Pinto, C., Almeida, E., Gomes, F., Moreira, I., Fernandes, J., & Teixeira-Pinto, A. (2013). Semantic fluency and phonemic fluency: Regression-based norms for the Portuguese population. *Archives of Clinical Neuropsychology*. 10.1093/arclin/act001.
Cavanna, A. E., & Trimble, M. R. (2006). The precuneus: A review of its functional anatomy and behavioural correlates. *Brain*, *129*(3), 564-583.
Celone, K. A., Calhoun, V. D., Dickerson, B. C., Atri, A., Chua, E. F., Miller, S. L., Depeau, K., Rentz, D. M., Selkoe, D. J., Blacker, D., & Albert, M. S. (2006). Alterations in memory networks in mild cognitive impairment and Alzheimer's disease: an independent component analysis. *Journal of Neuroscience*, *26*(40), 10222-10231.
Cepeda, N. J., Pashler, H., Vul, E., Wixted, J. T., & Rohrer, D. (2006). Distributed practice in verbal recall tasks: A review and quantitative synthesis. *Psychological Bulletin*, *132*(3), 354-380.
Charles, S. T. (2010). Strength and vulnerability integration: a model of emotional well-being across adulthood. *Psychological Bulletin*, *136*(6), 1068-1091.

Chen, J., Myerson, J., & Hale, S. (2002). Age-related dedifferentiation of visuospatial abilities. *Neuropsychologia, 40*, 2050-2056.
Cherrier, M. M., Mendez, M., & Perryman, K. (2001). Route learning performance in Alzheimer disease patients. *Cognitive and Behavioral Neurology*, *14*(3), 159-168.
Chhatwal, J. P., Schultz, A. P., Johnson, K., Benzinger, T. L., Jack, C., Ances, B. M., & Marcus, D. S. (2013). Impaired default network functional connectivity in autosomal dominant Alzheimer disease. *Neurology*, *81*(8), 736-744.
Choi, S., & Bowerman, M. (1991). Learning to express motion events in English and Korean: The influence of language-specific lexicalization patterns. *Cognition*, *41*(1-3), 83-121.
Choi, S., McDonough, L., Bowerman, M., & Mandler, J. M. (1999). Early sensitivity to language-specific spatial categories in English and Korean. *Cognitive Development*, *14*(2), 241-268.
Clancy Dollinger, S. M. (1995). Mental rotation performance: Age, sex, and visual field differences. *Developmental Neuropsychology*, *11*(2), 215-222.
Colcombe, S., & Kramer, A. F. (2003). Fitness effects on the cognitive function of older adults: A meta-analytic study. *Psychological Science, 14*: 125.
Conder, J., Fridriksson, J., Baylis, G. C., Smith, C. M., Boiteau, T. W., & Almor, A. (2017). Bilateral parietal contributions to spatial language. *Brain and Language, 164,* 16-24.
Conlon, E., & Herkes, K. (2008). Spatial and temporal processing in healthy aging: Implications for perceptions of driving skills. *Aging, Neuropsychology, and Cognition, 15*(4), 446-470.
Contreras, M. J., Colom, R., Hernández, J. M., & Santacreu, J. (2003). Is static spatial performance distinguishable from dynamic spatial performance? A latent-variable analysis. *The Journal of General Psychology*, *130*(3), 277-288.
Contreras, M. J., Colom, R., Shih, P. C., Alava, M. J., & Santacreu, J. (2001). Dynamic spatial performance: Sex and educational differences. *Personality and Individual differences*, *30*(1), 117-126.
Contreras, M. J., Rubio, V. J., Peña, D., Colom, R., & Santacreu, J. (2007). Sex differences in dynamic spatial ability: The unsolved question of performance factors. *Memory & Cognition*, *35*(2), 297-303.
Cook, R. D. (1977). Detection of influential observation in linear regression. *Technometrics*, *19*(1), 15-18.
Cornoldi, C., Bassani, C., Berto, R., & Mammarella, N. (2007). Aging and the intrusion superiority effect in visuo-spatial working memory. *Aging, Neuropsychology, and Cognition*, *14*(1), 1-21.
Costa, A., Bagoj, E., Monaco, M., Zabberoni, S., De Rosa, S., Papantonio, A. M., Mundi, C., Caltagirone, C., & Carlesimo, G.A. (2014). Standardization and normative data obtained in the Italian population for a new verbal fluency instrument, the phonemic/semantic alternate fluency test. *Neurological Sciences*, *35*(3), 365-372.
Cotelli, M., Manenti, R., Cappa, S. F., Geroldi, C., Zanetti, O., Rossini, P. M., & Miniussi, C. (2006). Effect of transcranial magnetic stimulation on action naming in patients with Alzheimer disease. *Archives of Neurology*, *63*(11), 1602-1604.
Cotelli, M., Manenti, R., Cappa, S. F., Zanetti, O., & Miniussi, C. (2008). Transcranial magnetic stimulation improves naming in Alzheimer disease patients at different stages of cognitive decline. *European Journal of Neurology*, *15*(12), 1286-1292.
Coventry, K. R. (1998). Spatial prepositions, functional relations and lexical specification. In P. Olivier and K.-P. Gapp (Eds.), *Representation and processing of spatial expressions* (pp. 247-262). Mahwah, NJ: Erlbaum
Coventry, K. R., Carmichael, R., & Garrod, S. C. (1994). Spatial prepositions, object-specific function, and task requirements. *Journal of Semantics*, *11*(4), 289-309.
Coventry, K. R., & Garrod, S. C. (2004). *Saying, seeing and acting; The psychological semantics of spatial prepositions*. Hove: Psychology Press.

Coventry, K., & Garrod, S. (2005). Towards a classification of extra-geometric influences on the comprehension of spatial prepositions. In: L. Carlson, E. van der Zee (Eds.), *Functional features in language and space: Explorations in language and space* (pp. 149-162). Oxford: Oxford University Press.

Coventry, K. R., Lynott, D., Cangelosi, A., Monrouxe, L., Joyce, D., & Richardson, D. C. (2010). Spatial language, visual attention, and perceptual simulation. *Brain and Language*, *112*(3), 202-213.

Coventry, K. R., Griffiths, D., & Hamilton, C. J. (2014). Spatial demonstratives and perceptual space: Describing and remembering object location. *Cognitive Psychology, 69*, 46-70.

Coventry, K. R., & Prat-Sala, M. (2001). Object-specific function, geometry, and the comprehension of in and on. *European Journal of Cognitive Psychology*, *13*(4), 509-528.

Coventry, K. R., Prat-Sala, M., & Richards, L. (2001). The interplay between geometry and function in the comprehension of over, under, above, and below. *Journal of Memory and Language*, *44*(3), 376-398.

Coventry, K. R., Valdés, B., Castillo, A., & Guijarro-Fuentes, P. (2008). Language within your reach: Near-far perceptual space and spatial demonstratives. *Cognition*, *108*(3), 889-895.

Craik, F. I., & Bialystok, E. (2006). Cognition through the lifespan: Mechanisms of change. *Trends in Cognitive Sciences*, *10*(3), 131-138.

Craik, F. I. M., & Jennings, J. M. (1992). Human memory. In F. I. M. Craik & T. A. Salthouse (Eds.), *The handbook of aging and cognition* (pp. 51-110). Hillsdale, NJ: Lawrence Erlbaum Associates.

Craton, L. G., Elicker, J., Plumert, J. M., & Pick, H. L. (1990). Children's use of frames of reference in communication of spatial location. *Child Development*, *61*(5), 1528-1543.

Crawford, L. E., Regier, T., & Huttenlocher, J. (2000). Linguistic and non-linguistic spatial categorization. *Cognition*, *75*(3), 209-235.

Croot, K., Hodges, J. R., Xuereb, J., & Patterson, K. (2000). Phonological and articulatory impairment in Alzheimer's disease: A case series. *Brain and Language*, *75*(2), 277-309.

Cumming, G. (2009). Inference by eye: reading the overlap of independent confidence intervals. *Statistics in Medicine*, *28*(2), 205-220.

Cushman, L., Stein, K., & Duffy, C. J. (2008). Detecting navigational deficits in cognitive aging and Alzheimer disease using virtual reality. *Neurology*, *71*(12), 888-895.

Dalla Barba, G. (1993). Confabulation: Knowledge and recollective experience. *Cognitive Neuropsychology*, *10*(1), 1-20.

Dalla Barba, G., & Boissé, M. F. (2010). Temporal consciousness and confabulation: Is the medial temporal lobe “temporal”? *Cognitive Neuropsychiatry*, *15*(1-3), 95-117.

Dalla Barba, G., Mantovan, M. C., Traykov, L. T., Rieu, D., Laurent, A., Ermani, M., & Devouche, E. (2002). The functional locus of intrusions: encoding or retrieval? *Journal of Clinical and Experimental Neuropsychology*, *24*(5), 633-641.

Dalla Barba, G. D., Nedjam, Z., & Dubois, B. (1999). Confabulation, executive functions, and source memory in Alzheimer's disease. *Cognitive Neuropsychology*, *16*(5), 385-398.

Dalla Barba, G., Parlato, V., Iavarone, A., & Boller, F. (1995). Anosognosia, intrusions and ‘frontal’functions in Alzheimer's disease and depression. *Neuropsychologia*, *33*(2), 247-259.

Damasio, H., Grabowski, T. J., Tranel D., Ponto, L. L. B., Hichwa, R. D., & Damasio, A. R. (2001). Neural correlates of naming actions and of naming spatial relations. *NeuroImage, 13*, 1053-1064.

Damasio, A. R., & Tranel, D. (1993). Nouns and verbs are retrieved with differently distributed neural systems. *Proceedings of the National Academy of Sciences*, *90*(11), 4957-4960.

Damian, A. M., Jacobson, S. A., Hentz, J. G., Belden, C. M., Shill, H. A., Sabbagh, M. N., Caviness, J. N., & Adler, C. H. (2011). The Montreal Cognitive Assessment and the Mini-Mental State Examination as screening instruments for cognitive impairment: Item analyses and threshold scores. *Dementia and Geriatric Cognitive Disorders*, *31*(2), 126-131.

Damoiseaux, J. S., Beckmann, C. F., Arigita, E. S., Barkhof, F., Scheltens, P., Stam, C. J., Smith, S. M., & Rombouts, S. A. R. B. (2008). Reduced resting-state brain activity in the “default network” in normal aging. *Cerebral Cortex*, *18*(8), 1856-1864.
Daniele, A., Giustolisi, L., Silveri, M. C., Colosimo, C., & Gainotti, G. (1994). Evidence for a possible neuroanatomical basis for lexical processing of nouns and verbs. *Neuropsychologia*, *32*(11), 1325-1341.
David, N., Bewernick, B. H., Cohen, M. X., Newen, A., Lux, S., Fink, G. R., Shah, N. J., & Vogeley, K. (2006). Neural representations of self versus other: Visual-spatial perspective taking and agency in a virtual ball-tossing game. *Journal of Cognitive Neuroscience*, *18*(6), 898-910.
Davis, C., Heidler-Gary, J., Gottesman, R. F., Crinion, J., Newhart, M., Moghekar, A., Soloman, D., Rigamonti, D., Cloutman, L., & Hillis, A. E. (2010). Action versus animal naming fluency in subcortical dementia, frontal dementias, and Alzheimer's disease. *Neurocase*, *16*(3), 259-266.
Davis, S. W., Dennis, N. A., Daselaar, S. M., Fleck, M. S., & Cabeza, R. (2008). Que PASA? The posterior–anterior shift in aging. *Cerebral Cortex*, *18*(5), 1201-1209.
Deary, I. J., Corley, J., Gow, A. J., Harris, S. E., Houlihan, L. M., Marioni, R. E., Penke, L., Rafnsson, S. B., & Starr, J. M. (2009). Age-associated cognitive decline. *British Medical Bulletin*, *92*(1), 135-152.
Deary, I. J., Johnson, W., & Starr, J. M. (2010). Are processing speed tasks biomarkers of cognitive aging? *Psychology and Aging*, *25*(1), 219-228.
De Anna, F., Attali, E., Freynet, L., Foubert, L., Laurent, A., Dubois, B., & Dalla Barba, G. (2008). Intrusions in story recall: When over-learned information interferes with episodic memory recall. Evidence from Alzheimer's disease. *Cortex*, *44*(3), 305-311.
De Beni, R., Pazzaglia, F., & Gardini, S. (2006). The role of mental rotation and age in spatial perspective-taking tasks: When age does not impair perspective-taking performance. *Applied Cognitive Psychology*, *20*(6), 807-821.
Delbeuck, X., Debachy, B., Pasquier, F., & Moroni, C. (2013). Action and noun fluency testing to distinguish between Alzheimer's disease and dementia with Lewy bodies. *Journal of Clinical and Experimental Neuropsychology*, *35*(3), 259-268.
Delis, D. C., Kramer, J. H., Kaplan, E., & Ober, B. A. (2000). *California Verbal Learning Test-II.* San Antonio, TX: Psychological Corporation.
Della Sala, S., Gray, C., Baddeley, A., Allamano, N., & Wilson, L. (1999). Pattern span: A tool for unwelding visuo–spatial memory. *Neuropsychologia*, *37*(10), 1189-1199.
De Luca, C. R., Wood, S. J., Anderson, V., Buchanan, J. A., Proffitt, T. M., Mahony, K., & Pantelis, C. (2003). Normative data from the CANTAB. I: Development of executive function over the lifespan. *Journal of Clinical and Experimental Neuropsychology*, *25*(2), 242-254.
De Reuck, J., Deramecourt, V., Cordonnier, C., Pasquier, F., Leys, D., Maurage, C. A., & Bordet, R. (2016). The incidence of post-mortem neurodegenerative and cerebrovascular pathology in mixed dementia. *Journal of the Neurological Sciences*, *366*, 164-166.
Dermody, N., Hornberger, M., Piguet, O., Hodges, J. R., & Irish, M. (2016). Prospective memory impairments in Alzheimer’s disease and behavioral variant frontotemporal dementia: Clinical and neural correlates. *Journal of Alzheimer's Disease*, *50*(2), 425-441.
De Simone, L., Tomasino, B., Marusic, N., Eleopra, R., & Rumiati, R. I. (2013). The effects of healthy aging on mental imagery as revealed by egocentric and allocentric mental spatial transformations. *Acta Psychologica*, *143*(1), 146-156.
Desgranges, B., Baron, J. C., Giffard, B., Chételat, G., Lalevée, C., Viader, F., de la Sayette, V. and Eustache, F. (2002). The neural basis of intrusions in free recall and cued recall: a PET study in Alzheimer's disease. *Neuroimage*, *17*(3),1658-1664.
Dessalegn, B., & Landau, B. (2013). Interaction between language and vision: It’s momentary, abstract, and it develops. *Cognition*, *127*(3), 331-344.

Devlin, A. L., & Wilson, P. H. (2010). Adult age differences in the ability to mentally transform object and body stimuli. *Aging, Neuropsychology, and Cognition*, *17*(6), 709-729.
Diamond, A. (2013). Executive functions. *Annual Review of Psychology, 64,* 135-168.
Dickerson, B. C., & Sperling, R. A. (2008). Functional abnormalities of the medial temporal lobe memory system in mild cognitive impairment and Alzheimer's disease: Insights from functional MRI studies. *Neuropsychologia*, *46*(6), 1624-1635.
Didic, M., Barbeau, E. J., Felician, O., Tramoni, E., Guedj, E., Poncet, M., & Ceccaldi, M. (2011). Which memory system is impaired first in Alzheimer's disease? *Journal of Alzheimer's Disease*, *27*(1), 11-22.
Dijkstra, K., Bourgeois, M. S., Allen, R. S., & Burgio, L. D. (2004). Conversational coherence: Discourse analysis of older adults with and without dementia. *Journal of Neurolinguistics*, *17*(4), 263-283.
Di Marco, L. Y., Venneri, A., Farkas, E., Evans, P. C., Marzo, A., & Frangi, A. F. (2015). Vascular dysfunction in the pathogenesis of Alzheimer's disease - A review of endothelium-mediated mechanisms and ensuing vicious circles. *Neurobiology of Disease*, *82*, 593-606.
Diniz, B. S., Butters, M. A., Albert, S. M., Dew, M. A., & Reynolds, C. F. (2013). Late-life depression and risk of vascular dementia and Alzheimer's disease: Systematic review and meta-analysis of community-based cohort studies. *The British Journal of Psychiatry*, *202*(5), 329-335.
Driscoll, I., Hamilton, D. A., Yeo, R. A., Brooks, W. M., and Sutherland, R. J. (2005). Virtual navigation in humans: the impact of age, sex, and hormones on place learning. *Hormones and Behavior*, 47, 326-335.
Driscoll, I., Howard, S. R., Stone, J. C., Monfils, M. H., Tomanek, B., Brooks, W. M., & Sutherland, R. J. (2006). The aging hippocampus: A multi-level analysis in the rat. *Neuroscience,* 139, 1173-1185.
Doeller, C. F., King, J. A., & Burgess, N. (2008). Parallel striatal and hippocampal systems for landmarks and boundaries in spatial memory. *Proceedings of the National Academy of Sciences, 105*, 5915-5920.
Druks, J., Masterson, J., Kopelman, M., Clare, L., Rose, A., & Rai, G. (2006). Is action naming better preserved (than object naming) in Alzheimer's disease and why should we ask? *Brain and Language*, *98*(3), 332-340.
Dubois, B., Feldman, H.H., Jacova, C., Hampel, H., Molinuevo, J.L., Blennow, K., DeKosky, S.T., Gauthier, S., Selkoe, D., Bateman, R. and Cappa, S. (2014). Advancing research diagnostic criteria for Alzheimer's disease: The IWG-2 criteria. *The Lancet Neurology*, *13*(6), 614-629.
Duchek, J. M., Balota, D. A., & Cortese, M. (2006). Prospective memory and apolipoprotein E in healthy aging and early stage Alzheimer's disease. *Neuropsychology*, *20*(6), 633.
Dunlosky, J., & Hertzog, C. (2001). Measuring strategy production during associative learning: The relative utility of concurrent versus retrospective reports. *Memory & Cognition*, *29*(2), 247-253.
Han, S. D., Nguyen, C. P., Stricker, N. H., & Nation, D. A. (2017). Detectable neuropsychological differences in early preclinical Alzheimer's disease: A meta-analysis. *Neuropsychology Review*, in press.
Edgin, J. O., & Pennington, B. F. (2005). Spatial cognition in autism spectrum disorders: Superior, impaired, or just intact? *Journal of Autism and Developmental Disorders*, *35*(6): 729.
Edwards, E., Nagarajan, S. S., Dalal, S. S., Canolty, R. T., Kirsch, H. E., Barbaro, N. M., & Knight, R. T. (2010). Spatiotemporal imaging of cortical activation during verb generation and picture naming. *Neuroimage*, *50*(1), 291-301.
Ekstrom, A. D., Arnold, A. E. G. F., & Iaria, G. (2014). A critical review of the allocentric spatial representation and its neural underpinnings: toward a network-based perspective. *Frontiers in Human Neuroscience*, *8*: 803.

El Haj, M., Antoine, P., Amouyel, P., Lambert, J. C., Pasquier, F., & Kapogiannis, D. (2016). Apolipoprotein E (APOE) ε4 and episodic memory decline in Alzheimer's disease: A review. *Ageing Research Reviews*, *27*, 15-22.
El Haj, M., & Kessels, R. P. (2013). Context memory in Alzheimer's disease. *Dementia and Geriatric Cognitive Disorders*, *3*(1), 342-350.
Emery, V. O. B. (2000). Language impairment in dementia of the Alzheimer type: A hierarchical decline? *The International Journal of Psychiatry in Medicine*, *30*(2), 145-164.
Epley, N., Morewedge, C. K., & Keysar, B. (2004). Perspective taking in children and adults: Equivalent egocentrism but differential correction. *Journal of Experimental Social Psychology*, *40*(6), 760-768.
Esfahani-Bayerl, N., Finke, C., Braun, M., Düzel, E., Heekeren, H.R., Holtkamp, M., Hasper, D., Storm, C., & Ploner, C.J. (2016). Visuo-spatial memory deficits following medial temporal lobe damage: A comparison of three patient groups. *Neuropsychologia*, *81*, 168-179.
Etchamendy, N., & Bohbot, V. D. (2007). Spontaneous navigational strategies and performance in the virtual town. *Hippocampus*, *17*, 595-599.
European Commission, Eurostat (2015). *Europe in figures – Eurostat yearbook.* On-line source: http://ec.europa.eu/eurostat/statistics-explained/.
Eyler, L. T., Sherzai, A., Kaup, A. R., & Jeste, D. V. (2011). A review of functional brain imaging correlates of successful cognitive aging. *Biological Psychiatry*, *70*(2), 115-122.
Facal, D., Juncos-Rabadán, O., Rodríguez, M. S., & Pereiro, A. X. (2012). Tip-of-the-tongue in aging: Influence of vocabulary, working memory and processing speed. *Aging Clinical and Experimental Research*, *24*(6), 647-656.
Fastenau, P. S., Denburg, N. L., & Hufford, B. J. (1999). Adult norms for the Rey-Osterrieth Complex Figure Test and for supplemental recognition and matching trials from the Extended Complex Figure Test. *The Clinical Neuropsychologist*, *13*(1), 30-47.
Faust, M. E., Balota, D. A., & Multhaup, K. S. (2004). Phonological blocking during picture naming in dementia of the Alzheimer type. *Neuropsychology*, *18*(3), 526.
Féart, C., Samieri, C., & Barberger-Gateau, P. (2010). Mediterranean diet and cognitive function in older adults. *Current Opinion in Clinical Nutrition and Metabolic Care*, *13*(1), 14-18.
Feist, M. I. (2009). Spatial cognition through the lens of spatial language. *Cognitive Processing*, *10*(2), 212-214.
Feist, M. I., & Gentner, D. (2007). Spatial language influences memory for spatial scenes. *Memory & Cognition*, *35*(2), 283-296.
Feng, J., Spence, I., & Pratt, J. (2007). Playing an action video game reduces gender differences in spatial cognition. *Psychological Science*, *18*(10), 850-855.
Ferrara, K., Hirsh-Pasek, K., Newcombe, N. S., Golinkoff, R. M., & Lam, W. S. (2011). Block talk: Spatial language during block play. *Mind, Brain, and Education*, *5*(3), 143-151.
Field, A. (2009). *Discovering statistics using SPSS.* London: SAGE.
Filimon, F. (2015). Are all spatial reference frames egocentric? Reinterpreting evidence for allocentric, object-centered, or world-centered reference frames. *Frontiers in Human Neuroscience, 9*: 648.
Finkel, D., Reynolds, C. A., McArdle, J. J., & Pedersen, N. L. (2007). Age changes in processing speed as a leading indicator of cognitive aging. *Psychology and Aging*, *22*(3), 558-568.
Fiore, F., Borella, E., Mammarella, I. C., & Cornoldi, C. (2011). Mental imagery in a visuospatial working memory task and modulation of activation. *Journal of Cognitive Psychology*, *23*(1), 52-59.
Fiore, F., Borella, E., Mammarella, I. C., & De Beni, R. (2012). Age differences in verbal and visuo-spatial working memory updating: Evidence from analysis of serial position curves. *Memory*, *20*(1), 14-27.
Fisk, J. E., & Sharp, C. A. (2004). Age-related impairment in executive functioning: Updating, inhibition, shifting, and access. *Journal of Clinical and Experimental Neuropsychology*, *26*(7), 874-890.

Fjell, A. M., McEvoy, L., Holland, D., Dale, A. M., Walhovd, K. B., & Alzheimer's Disease Neuroimaging Initiative. (2014). What is normal in normal aging? Effects of aging, amyloid and Alzheimer's disease on the cerebral cortex and the hippocampus. *Progress in Neurobiology*, *117*, 20-40.

Fjell, A.M., Westlye, L.T., Amlien, I., Espeseth, T., Reinvang, I., Raz, N., Agartz, I., Salat, D.H., Greve, D.N., Fischl, B., & Dale, A.M. (2009). High consistency of regional cortical thinning in aging across multiple samples. *Cerebral Cortex*, p.bhn232.

Franzen, M. D., Haut, M. W., Rankin, E., & Keefover, R. (1995). Empirical comparison of alternate forms of the Boston Naming Test. *The Clinical Neuropsychologist*, *9*, 225-229.

Frisoni, G. B., Fox, N. C., Jack, C. R., Scheltens, P., & Thompson, P. M. (2010). The clinical use of structural MRI in Alzheimer disease. *Nature Reviews Neurology, 6*(2), 67-77.

Foster, T. C., Defazio, R. A., & Bizon, J. L. (2012). Characterizing cognitive aging of spatial and contextual memory in animal models. *Frontiers in Aging Neuroscience, 4*: 12.

Fox, C., Maidment, I., Moniz-Cook, E., White, J., Thyrian, J. R., Young, J., Katona, C., & Chew-Graham, C. A. (2013). Optimising primary care for people with dementia. *Mental Health in Family Medicine*, *10*(3), p.143-151.

Fung, T. D., Chertkow, H., Murtha, S., Whatmough, C., Péloquin, L., Whitehead, V., & Templeman, F. D. (2001). The spectrum of category effects in object and action knowledge in dementia of the Alzheimer's type. *Neuropsychology*, *15*(3), 371.

Gainotti, G., Silveri, M. C., Daniel, A., & Giustolisi, L. (1995). Neuroanatomical correlates of category-specific semantic disorders: A critical survey. *Memory*, *3*(3-4), 247-263.

Galati, G., Pelle, G., Berthoz, A., & Committeri, G. (2010). Multiple reference frames used by the human brain for spatial perception and memory. *Experimental Brain Research*, *206*(2), 109-120.

Gallagher, M., & Koh, M. T. (2011). Episodic memory on the path to Alzheimer's disease. *Current Opinion in Neurobiology, 21*(6), 929-934.

Gallistel, C. R. (2002). Language and spatial frames of reference in mind and brain. *Trends in Cognitive Sciences*, *6*(8), 321-322.

Galton, C. J., Patterson, K., Xuereb, J. H., & Hodges, J. R. (2000). Atypical and typical presentations of Alzheimer's disease: a clinical, neuropsychological, neuroimaging and pathological study of 13 cases. *Brain*, *123*(3), 484-498.

Garn, C. L., Allen, M. D., & Larsen, J. D. (2009). An fMRI study of sex differences in brain activation during object naming. *Cortex*, *45*(5), 610-618.

Garrod, S., Ferrier, G., & Campbell, S. (1999). In and on: Investigating the functional geometry of spatial prepositions. *Cognition*, *72*(2), 167-189.

Gates, N. J., & Kochan, N. A. (2015). Computerized and on-line neuropsychological testing for late-life cognition and neurocognitive disorders: Are we there yet? *Current Opinion in Psychiatry*, *28*(2), 165-172.

Gauthier, C. T., Duyme, M., Zanca, M., & Capron, C. (2009). Sex and performance level effects on brain activation during a verbal fluency task: A functional magnetic resonance imaging study. *Cortex*, *45*(2), 164-176.

Gazova, I., Laczó, J., Rubinova, E., Mokrisova, I., Hyncicova, E., Andel, R., Vyhnalek, M., Sheardova, K., Coulson, E.J. and Hort, J. (2013). Spatial navigation in young versus older adults. *Frontiers in Aging Neuroscience, 5*: 94.

Gentner, D., Ozyürek, A., Gürcanli, O., & Goldin-Meadow, S. (2013). Spatial language facilitates spatial cognition: Evidence from children who lack language input. *Cognition*, *127*(3), 318-330.

Giannakou, M., & Kosmidis, M. H. (2006). Cultural appropriateness of the Hooper visual organization test? Greek normative data. *Journal of Clinical and Experimental Neuropsychology, 28*(6), 1023-1029.

Gladsjo, J. A., Schuman, C. C., Evans, J. D., Peavy, G. M., Miller, S. W., & Heaton, R. K. (1999). Norms for letter and category fluency: Demographic corrections for age, education, and ethnicity. *Assessment*, *6*(2), 147-178.
Gogtay, N., Nugent, T. F., Herman, D. H., Ordonez, A., Greenstein, D., Hayashi, K. M., Clasen, L., Toga, A. W., Giedd, J. N., Rapoport, J. L., & Thompson, P. M. (2006). Dynamic mapping of normal human hippocampal development. *Hippocampus*, *16*(8), 664-672.
Göksun, T., Lehet, M., Malykhina, K., & Chatterjee, A. (2013). Naming and gesturing spatial relations: Evidence from focal-brain injured individuals. *Neuropsychologia, 51*(8), 1518-1527.
Golby, A., Silverberg, G., Race, E., Gabrieli, S., O'shea, J., Knierim, K., Stebbins, G., & Gabrieli, J. (2005). Memory encoding in Alzheimer's disease: An fMRI study of explicit and implicit memory. *Brain*, *128*(4), 773-787.
Golden, C. J. (1976). Identification of brain disorders by the Stroop Color and Word Test. *Journal of Clinical Psychology*, *32*(2), 654-658.
Goodale, M. A., & Milner, A. D. (1992). Separate visual pathways for perception and action. *Trends in Neurosciences*, *15*(1), 20-25.
Goral, M. (2004). First-language decline in healthy aging: Implications for attrition in bilingualism. *Journal of Neurolinguistics*, *17*(1), 31-52.
Goulet, P., Ska, B., & Kahn, H. J. (1994). Is there a decline in picture naming with advancing age? *Journal of Speech and Hearing Research, 37*, 629-644.
Grady, C. L. (2008). Cognitive neuroscience of aging. *Annals of the New York Academy of Sciences*, *1124*, 127-144.
Gravetter, F., & Wallnau, L. (2014). *Essentials of statistics for the behavioral sciences* (8th ed.). Belmont, CA: Wadsworth.
Graves, R. E., Bezeau, S. C., Fogarty, J., & Blair, R. (2004). Boston naming test short forms: A comparison of previous forms with new item response theory based forms. *Journal of Clinical and Experimental Neuropsychology, 26*(7), 891-902.
Greenwood, P. M., Parasuraman, R., & Haxby, J. V. (1993). Changes in visuospatial attention over the adult lifespan. *Neurospychologia, 31*(5), 471-485.
Greicius, M. D., Srivastava, G., Reiss, A. L., & Menon, V. (2004). Default-mode network activity distinguishes Alzheimer's disease from healthy aging: evidence from functional MRI. *Proceedings of the National Academy of Sciences of the United States of America*, *101*(13), 4637-4642.
Gunning-Dixon, F. M., Brickman, A. M., Cheng, J. C., & Alexopoulos, G. S. (2009). Aging of cerebral white matter: A review of MRI findings. *International Journal of Geriatric Psychiatry*, *24*(2), 109-117.
Gutchess, A. H., Welsh, R. C., Hedden, T., Bangert, A., Minear, M., Liu, L. L., & Park, D. C. (2005). Aging and the neural correlates of successful picture encoding: frontal activations compensate for decreased medial-temporal activity. *Journal of Cognitive Neuroscience*, *17*(1), 84-96.
Gyselinck, V., Meneghetti, C., Bormetti, M., Orriols, E., Piolino, P., & De Beni, R. (2013). Considering spatial ability in virtual route learning in early aging. *Cognitive Processing*, *14*(3), 309-316.
Hadad, B. S. (2012). Sensitivity of spatial integration to perceptual cues is preserved in healthy aging. *Vision Research*, *60*, 1-6.
Hale, S., Rose, N. S., Myerson, J., Strube, M. J., Sommers, M., Tye-Murray, N., & Spehar, B. (2011). The structure of working memory abilities across the adult life span. *Psychology and Aging*, *26*(1), 92-110.
Hamdan, A. C., & Hamdan, E. M. L. (2009). Effects of age and education level on the Trail Making Test in a healthy Brazilian sample. *Psychology & Neuroscience*, *2*(2), 199-203.
Hamilton, A. F. D. C., Brindley, R., & Frith, U. (2009). Visual perspective taking impairment in children with autistic spectrum disorder. *Cognition*, *113*(1), 37-44.

Hamilton, C. J. (1995). Beyond sex difference in visuo-spatial processing: The impact of gender trait possession. *British Journal of Psychology, 86*, 1-20.
Hampel, H., & Lista, S. (2016). Dementia: The rising global tide of cognitive impairment. *Nature Reviews Neurology*, *12*(3), 131-132.
Hampstead, B. M., Stringer, A. Y., Stilla, R. F., Amaraneni, A., & Sathian, K. (2011). Where did I put that? Patients with amnestic mild cognitive impairment demonstrate widespread reductions in activity during the encoding of ecologically relevant object-location associations. *Neuropsychologia*, *49*(9), 2349-2361.
Hannula, D. E., & Ranganath, C. (2008). Medial temporal lobe activity predicts successful relational memory binding. *Journal of Neuroscience*, *28*(1), 116-124.
Harper, L., Bouwman, F., Burton, E. J., Barkhof, F., Scheltens, P., O'Brien, J., Fox, N. C., Ridgway, G. R., & Schott, J. M. (2017). Patterns of atrophy in pathologically confirmed dementias: A voxelwise analysis. *Journal of Neurology, Neurosurgery, and Psychiatry*, in press.
Harris, I. M., Egan, G. F., Sonkkila, C., Tochon-Danguy, H. J., Paxinos, G., & Watson, J. D. (2000). Selective right parietal lobe activation during mental rotation. *Brain*, *123*(1), 65-73.
Harris, M. A., Wiener, J. M., & Wolbers, T. (2012). Aging specifically impairs switching to an allocentric navigational strategy. *Frontiers in Aging Neuroscience, 4*, 1-9.
Harris, M. A., & Wolbers, T. (2012). Ageing effects on path integration and landmark navigation. *Hippocampus, 22*, 1770-1780.
Harrison, J. E., Buxton, P., Husain, M., & Wise, R. (2000). Short test of semantic and phonological fluency: Normal performance, validity and test-retest reliability. *British Journal of Clinical Psychology*, *39*(2), 181-191.
Hartley, T., Bird, C.M., Chan, D., Cipolotti, L., Husain, M., Vargha-Khadem, F., & Burgess, N. (2007). The hippocampus is required for short-term topographical memory in humans. *Hippocampus, 17*(1), 34-48.
Hartley, T., & Harlow, R. (2012). An association between human hippocampal volume and topographical memory in healthy young adults. *Frontiers in Human Neuroscience, 338*, 1-11.
Hartshorne, J. K., & Germine, L. T. (2015). When does cognitive functioning peak? The asynchronous rise and fall of different cognitive abilities across the life span. *Psychological Science, 26*(4), 433-443.
Havas, V., Gabarrós, A., Juncadella, M., Rifa-Ros, X., Plans, G., Acebes, J.J., de Diego Balaguer, R., & Rodríguez-Fornells, A. (2015). Electrical stimulation mapping of nouns and verbs in Broca's area. *Brain and Language, 145*, 53-63.
Haun, D. B. M., Rapold, C. J., Janzen, G., & Levinson, S. C. (2011). Plasticity of human spatial cognition: Spatial language and cognition covary across cultures. *Cognition*, *119*(1), 70-80.
Hawkins, K. A., & Bender, S. (2002). Norms and the relationship of Boston Naming Test performance to vocabulary and education: A review. *Aphasiology, 16*(12), 1143-1153.
Haxby, J. V., Grady, C. L., Koss, E., Horwitz, B., Heston, L., Schapiro, M., Friedland, R. P., & Rapoport, S. I. (1990). Longitudinal study of cerebral metabolic asymmetries and associated neuropsychological patterns in early dementia of the Alzheimer type. *Archives of Neurology, 47*(7), 753-760.
Hayward, W. G., & Tarr, M. J. (1995). Spatial language and spatial representation. *Cognition, 55*(1), 39-84.
Head, D., & Isom, M. (2010). Age effects on wayfinding and route learning skills. *Behavioural Brain Research*, *209*(1), 49-58.
Hedden, T., & Gabrieli, J. D. (2004). Insights into the ageing mind: A view from cognitive neuroscience. *Nature Reviews Neuroscience*, *5*(2), 87-96.
Hegarty, M., Montello, D. R., Richardson, A. E., Ishikawa, T., & Lovelace, K. (2006). Spatial abilities at different scales: Individual differences in aptitude-test performance and spatial-layout learning. *Intelligence*, *34*(2), 151-176.

Hegarty, M. Richardson, A. E., Montello, D. R., Lovelace, K & Subbiah, I. (2002). Development of a self-report measure of environmental spatial ability. *Intelligence*, 30, 425-447.
Hegarty, M., & Waller, D. (2004). A dissociation between mental rotation and perspective taking spatial abilities. *Intelligence, 32*, 175-191.
Hegarty, M., & Waller, D. (2005). Individual differences in spatial abilities. In Shah, P., & Miyake, A. (Eds.), *The Cambridge handbook of visuospatial thinking* (pp. 121-169). Cambridge: Cambridge University Press.
Henderson, A. S., Jorm, A. F., Korten, A. E., Jacomb, P., Christensen, H., & Rodgers, B. (1998). Symptoms of depression and anxiety during adult life: evidence for a decline in prevalence with age. *Psychological Medicine*, *28*(06), 1321-1328.
Heneka, M. T., Carson, M. J., El Khoury, J., Landreth, G. E., Brosseron, F., Feinstein, D. L., & Herrup, K. (2015). Neuroinflammation in Alzheimer's disease. *The Lancet Neurology*, *14*(4), 388-405.
Henry, J. D., & Crawford, J. R. (2004). A meta-analytic review of verbal fluency performance following focal cortical lesions. *Neuropsychology*, *18*(2), 284-295.
Henry, J. D., Crawford, J. R., & Phillips, L. H. (2004). Verbal fluency performance in dementia of the Alzheimer's type: A meta-analysis. *Neuropsychologia*, *42*(9), 1212-1222.
Heo, S., Prakash, R. S., Voss, M. W., Erickson, K. I., Ouyang, C., Sutton, B. P., & Kramer, A. F. (2010). Resting hippocampal blood flow, spatial memory and aging. *Brain Research*, *1315*, 119-127.
Hernandez, A. E., Dapretto, M., Mazziotta, J., & Bookheimer, S. (2001). Language switching and language representation in Spanish–English bilinguals: An fMRI study. *NeuroImage*, *14*(2), 510-520.
Herskovits, A. (1986). *Language and spatial cognition: An interdisciplinary study of the prepositions in English.* Cambridge: Cambridge University Press.
Herskovits, A. (1997). Language, spatial cognition, and vision. In Stock, O. (Ed.) *Temporal and spatial reasoning* (pp. 155-202). Boston: Kluwer.
Hertzog, C., & Rypma, B. (1991). Age differences in components of mental-rotation task performance. *Bulletin of the Psychonomic Society*, *29*(2), 209-212.
Hirschfeld, G., & Zwitserlood, P. (2011). How vision is shaped by language comprehension –Top-down feedback based on low-spatial frequencies. *Brain Research*, *1377*, 78–83.
Hodges, J. R., & Patterson, K. (1995). Is semantic memory consistently impaired early in the course of Alzheimer's disease? Neuroanatomical and diagnostic implications. *Neuropsychologia*, *33*(4), 441-459.
Hodges, J. R., Salmon, D. P., & Butters, N. (1992). Semantic memory impairment in Alzheimer's disease: failure of access or degraded knowledge? *Neuropsychologia*, *30*(4), 301-314.
Holden, H. M., & Gilbert, P. E. (2012). Less efficient pattern separation may contribute to age-related spatial memory deficits. *Frontiers in Aging Neuroscience*, *4*, 1-6.
Hoogendam, Y. Y., Hofman, A., van der Geest, J. N., van der Lugt, A., & Ikram, M. A. (2014). Patterns of cognitive function in aging: The Rotterdam Study. *European Journal of Epidemiology*, *29*(2), 133-140.
Hooper, E. H. (1983). *The Hooper Visual Organization Test manual.* Los Angeles: Western Psychological Services.
Hornberger, M., Piguet, O., Graham, A. J., Nestor, P. J., & Hodges, J. R. (2010). How preserved is episodic memory in behavioral variant frontotemporal dementia? *Neurology*, *74*(6), 472-479.
Hort, J., Laczó, J., Vyhnálek, M., Bojar, M., Bureš, J., & Vlček, K. (2007). Spatial navigation deficit in amnestic mild cognitive impairment. *Proceedings of the National Academy of Sciences*, *104*(10), 4042-4047.
Iachini, T., Iavarone, A., Senese, V. P., Ruotolo, F., & Ruggiero, G. (2009). Visuospatial memory in healthy elderly, AD and MCI: A review. *Current Aging Science*, *2*(1), 43-59.

Iachini, T., Ruggiero, G., & Ruotolo, F. (2009). The effect of age on egocentric and allocentric spatial frames of reference. *Cognitive Processing*, *10*(2), 222-224.
Iaria, G., Chen, J. K., Guariglia, C., Ptito, A., & Petrides, M. (2007). Retrosplenial and hippocampal brain regions in human navigation: Complementary functional contributions to the formation and use of cognitive maps. *European Journal of Neuroscience*, *25*(3), 890-899.
Iaria, G., Palermo, L., Committeri, G., & Barton, J. J. (2009). Age differences in the formation and use of cognitive maps. *Behavioural Brain Research*, *196*(2), 187-191.
Iaria, G., Petrides, M., Dagher, A., Pike, B., & Bohbot, V. D. (2003). Cognitive strategies dependent on the hippocampus and caudate nucleus in human navigation: Variability and change with practice. *The Journal of Neuroscience*, *23*(13), 5945-5952.
Inagaki, H., Meguro, K., Shimada, M., Ishizaki, J., Okuzumi, H., & Yamadori, A. (2002). Discrepancy between mental rotation and perspective-taking abilities in normal aging assessed by Piaget's three-mountain task. *Journal of Clinical and Experimental Neuropsychology*, *24*(1), 18-25.
Irish, M., Hornberger, M., Lah, S., Miller, L., Pengas, G., Nestor, P. J., & Piguet, O. (2011). Profiles of recent autobiographical memory retrieval in semantic dementia, behavioural-variant frontotemporal dementia, and Alzheimer's disease. *Neuropsychologia*, *49*(9), 2694-2702.
Irish, M., & Piolino, P. (2016). Impaired capacity for prospection in the dementias–Theoretical and clinical implications. *British Journal of Clinical Psychology*, *55*(1), 49-68.
Ivanoiu, A., Adam, S., Van der Linden, M., Salmon, E., Juillerat, A. C., Mulligan, R., & Seron, X. (2005). Memory evaluation with a new cued recall test in patients with mild cognitive impairment and Alzheimer’s disease. *Journal of Neurology*, *252*(1), 47-55.
Jack, C. R., Knopman, D. S., Jagust, W. J., Petersen, R. C., Weiner, M. W., Aisen, P. S., Shaw, L. M., Vemuri, P., Wiste, H. J., Weigand, S. D., & Lesnick, T. G. (2013). Tracking pathophysiological processes in Alzheimer's disease: An updated hypothetical model of dynamic biomarkers. *The Lancet Neurology*, *12*(2), 207-216.
Jack, C. R., Petersen, R. C., Xu, Y. C., Waring, S. C., O'Brien, P. C., Tangalos, E. G., Smith, G. E., Ivnik, R. J., & Kokmen, E. (1997). Medial temporal atrophy on MRI in normal aging and very mild Alzheimer's disease. *Neurology*, *49*(3), 786-794.
Jacobs, H. I., Gronenschild, E. H., Evers, E. A., Ramakers, I. H., Hofman, P. A., Backes, W. H., Jolles J., Verhey F. R., & Van Boxtel, M. P. (2015). Visuospatial processing in early Alzheimer’s disease: A multimodal neuroimaging study. *Cortex*, *64*, 394-406.
Jager, G., & Postma, A. (2003). On the hemispheric specialization for categorical and coordinate spatial relations: A review of the current evidence. *Neuropsychologia*, *41*(4), 504-515.
Jagust, W. (2013). Vulnerable neural systems and the borderland of brain aging and neurodegeneration. *Neuron*, *77*(2), 219-234.
Jansen, P., & Heil, M. (2009). Gender differences in mental rotation across adulthood. *Experimental Aging Research*, *36*, 94-104.
Jansen, P., & Kaltner, S. (2014). Object-based and egocentric mental rotation performance in older adults: the importance of gender differences and motor ability. *Aging, Neuropsychology, and Cognition*, *21*(3), 296-316.
Jedynak, B. M., Liu, B., Lang, A., Gel, Y., Prince, J. L., & Alzheimer's Disease Neuroimaging Initiative. (2015). A computational method for computing an Alzheimer's disease progression score; experiments and validation with the ADNI data set. *Neurobiology of Aging*, *36*, S178-S184.
Jenkins, L., Myerson, J., Joerding, J. A., & Hale, S. (2000). Converging evidence that visuospatial cognition is more age-sensitive than verbal cognition. *Psychology and Aging*, *15*(1), 157-175.
Jessen, F., Amariglio, R.E., Van Boxtel, M., Breteler, M., Ceccaldi, M., Chételat, G., Dubois, B., Dufouil, C., Ellis, K.A., Van Der Flier, W.M., & Glodzik, L. (2014). A conceptual framework for research on subjective cognitive decline in preclinical Alzheimer's disease. *Alzheimer's & Dementia*, *10*(6), 844-852.

Jessen, F., Wiese, B., Bachmann, C., Eifflaender-Gorfer, S., Haller, F., Kölsch, H., Luck, T., Mösch, E., van den Bussche, H., Wagner, M., & Wollny, A. (2010). Prediction of dementia by subjective memory impairment: Effects of severity and temporal association with cognitive impairment. *Archives of General Psychiatry*, *67*(4), 414-422.
Jheng, S. S., & Pai, M. C. (2009). Cognitive map in patients with mild Alzheimer's disease: A computer-generated arena study. *Behavioural brain research*, *200*(1), 42-47.
Johnston, J. R., & Slobin, D. I. (1979). The development of locative expressions in English, Italian, Serbo-Croatian and Turkish. *Journal of Child Language*, *6*(03), 529-545.
Jones, S., Livner, Å., & Bäckman, L. (2006). Patterns of prospective and retrospective memory impairment in preclinical Alzheimer's disease. *Neuropsychology*, *20*(2), 144.
Jorm, A. F. (2000). Does old age reduce the risk of anxiety and depression? A review of epidemiological studies across the adult life span. *Psychological Medicine*, *30*(01), 11-22.
Joubert, S., Brambati, S. M., Ansado, J., Barbeau, E. J., Felician, O., Didic, M., Lacombe, J., Goldstein, R., Chayer, C., & Kergoat, M. J. (2010). The cognitive and neural expression of semantic memory impairment in mild cognitive impairment and early Alzheimer's disease. *Neuropsychologia*, *48*(4), 978-988.
Juncos-Rabadán, O., Facal, D., Rodriguez, M. S., & Pereiro, A. X. (2010). Lexical knowledge and lexical retrieval in ageing: Insights from a tip-of-the-tongue (TOT) study. *Language and Cognitive Processes*, *25*(10), 1301-1334.
Jurado, M. B., & Rosselli, M. (2007). The elusive nature of executive functions: A review of our current understanding. *Neuropsychology Review*, *17*(3), 213-233.
Kalpouzos, G., Chételat, G., Landeau, B., Clochon, P., Viader, F., & Eustache, F. (2009). Structural and metabolic correlates of episodic memory in relation to the depth of encoding in normal aging. *Journal of Cognitive Neuroscience*, *21*(2), 372-389.
Kane, M. J., Hambrick, D. Z., Tuholski, S. W., Wilhelm, O., Payne, T. W., & Engle, R. W. (2004). The generality of working memory capacity: A latent-variable approach to verbal and visuospatial memory span and reasoning. *Journal of Experimental Psychology: General*, *133*(2), 189-217.
Kaplan, E., Goodglass, H., & Weintraub, S. (2001). *Boston naming test.* Texas: Pro-Ed.
Katzman, R. (1993). Education and the prevalence of dementia and Alzheimer's disease. *Neurology*, *43*(1), 13-20.
Kemmerer, D. (2006). The semantics of space: Integrating linguistic typology and cognitive neuroscience. *Neuropsychologia*, *44*(9), 1607-1621.
Kemmerer, D., & Tranel, D. (2000). A double dissociation between linguistic and perceptual representations of spatial relationships. *Cognitive Neuropsychology, 17*(5), 393-414.
Kemps, E., & Newson, R. (2005). Patterns and predictors of adult age differences in mental imagery. *Aging, Neuropsychology, and Cognition*, *12*(1), 99-128.
Kemps, E., & Newson, R. (2006). Comparison of adult age differences in verbal and visuo-spatial memory: The importance of 'pure', parallel and validated measures. *Journal of Clinical and Experimental Neuropsychology*, *28*(3), 341-356.
Kennedy, K. M., & Raz, N. (2009). Aging white matter and cognition: differential effects of regional variations in diffusion properties on memory, executive functions, and speed. *Neuropsychologia*, *47*(3), 916-927.
Kessels, R. P. C., Feijen, J., & Postma, A. (2005). Implicit and explicit memory for spatial information in Alzheimer's disease. *Dementia and Geriatric Cognitive Disorders*, *20*(2-3), 184-191.
Kessels, R. P., Rijken, S., Banningh, W. J. W., Van Schuylenborgh-Van Es, N., & Rikkert, M. G. O. (2010). Categorical spatial memory in patients with mild cognitive impairment and Alzheimer dementia: Positional versus object-location recall. *Journal of the International Neuropsychological Society*, *16*(1), 200-204.
Kessler, K., & Rutherford, H. (2010). The two forms of visuo-spatial perspective taking are differently embodied and subserve different spatial prepositions. *Frontiers in Psychology, 1*: 213.

Kessler, K., & Thomson, L. A. (2010). The embodied nature of spatial perspective taking: embodied transformation versus sensorimotor interference. *Cognition*, *114*(1), 72-88.
Keys, B. A., & White, D. A. (2000). Exploring the relationship between age, executive abilities, and psychomotor speed. *Journal of the International Neuropsychological Society*, *6*(01), 76-82.
Khachaturian, Z. S. (2011). Revised criteria for diagnosis of Alzheimer’s disease: National Institute on Aging-Alzheimer's Association diagnostic guidelines for Alzheimer's disease. *Alzheimer's & dementia: The journal of the Alzheimer's Association*, *7*(3), 253-256.
Klatzky, R. L. (1998). Allocentric and egocentric spatial representations: Definitions, distinctions, and interconnections. In C. Freksa, C. Habel, & K. F. Wender (Eds.), *Spatial cognition-An interdisciplinary approach to representation and processing of spatial knowledge (Lecture notes in artificial intelligence, 1404),* pp. 1-17. Berlin: Spinger-Verlag.
Klencklen, G., Després, O., & Dufour, A. (2012). What do we know about aging and spatial cognition? Reviews and perspectives. *Ageing Research Reviews*, *11*(1), 123-35.
Koen, J. D., Borders, A. A., Petzold, M. T., & Yonelinas, A. P. (2017). Visual short-term memory for high resolution associations is impaired in patients with medial temporal lobe damage. *Hippocampus*, *27*(2), 184-193.
Koen, J. D., & Yonelinas, A. P. (2014). The effects of healthy aging, amnestic mild cognitive impairment, and Alzheimer’s disease on recollection and familiarity: A meta-analytic review. *Neuropsychology Review*, *24*(3), 332-354.
Konishi, K., & Bohbot, V. D. (2013). Spatial navigational strategies correlate with gray matter in the hippocampus of healthy older adults tested in a virtual maze. *Frontiers in Aging Neuroscience, 5*, 1-8.
Kosmidis, M. H., Vlahou, C. H., Panagiotaki, P., & Kiosseoglou, G. (2004). The verbal fluency task in the Greek population: Normative data, and clustering and switching strategies. *Journal of the International Neuropsychological Society*, *10*(02), 164-172.
Kosslyn, S. M. (1987). Seeing and imagining in the cerebral hemispheres: A computational approach. *Psychological Review*, *94*(2), 148.
Kozhevnikov, M., & Hegarty, M. (2001). A dissociation between object-manipulation and perspective-taking spatial abilities. *Memory & Cognition*, *29*, 745-756.
Kramer, J. H., Rosen, H. J., Du, A. T., Schuff, N., Hollnagel, C., Weiner, M. W., & Delis, D. C. (2005). Dissociations in hippocampal and frontal contributions to episodic memory performance. *Neuropsychology*, *19*(6), 799-805.
Kravitz, D. J., Saleem, K. S., Baker, C. I., & Mishkin, M. (2011). A new neural framework for visuospatial processing. *Nature Reviews Neuroscience*, *12*(4), 217-230.
Kroenke, K., Spintzer, R. L., Williams, J. B. (2001). The PHQ-9: Validity of a brief depression severity measure. *Journal of General Internal Medicine, 16*(9), 606-613.
Kuiper, J. S., Zuidersma, M., Voshaar, R. C. O., Zuidema, S. U., van den Heuvel, E. R., Stolk, R. P., & Smidt, N. (2015). Social relationships and risk of dementia: A systematic review and meta-analysis of longitudinal cohort studies. *Ageing Research Reviews*, *22*, 39-57.
Kumar, A., & Singh, A. (2015). A review on Alzheimer's disease pathophysiology and its management: An update. *Pharmacological Reports*, *67*(2), 195-203.
La Corte, V., Serra, M., Attali, E., Boisse, M. F., & Dalla Barba, G. (2010). Confabulation in Alzheimer’s disease and amnesia: A qualitative account and a new taxonomy. *Journal of the International Neuropsychological Society*, *16*(6), 967-974.
Laisney, M., Giffard, B., Belliard, S., De La Sayette, V., Desgranges, B., & Eustache, F. (2011). When the zebra loses its stripes: Semantic priming in early Alzheimer's disease and semantic dementia. *Cortex*, *47*(1), 35-46.
Lakusta, L., & Landau, B. (2005). Starting at the end: The importance of goals in spatial language. *Cognition*, *96*(1), 1-33.

Lakusta, L., & Landau, B. (2012). Language and memory for motion events: Origins of the asymmetry between source and goal paths. *Cognitive Science*, *36*(3), 517-544.
Lakusta, L., Wagner, L., O'Hearn, K., & Landau, B. (2007). Conceptual foundations of spatial language: Evidence for a goal bias in infants. *Language Learning and Development*, *3*(3), 179-197.
Lambrey, S., Doeller, C., Berthoz, A., & Burgess, N. (2011). Imagining being somewhere else: Neural basis of changing perspective in space. *Cerebral Cortex*, *22*(1), 166-174.
Landau, B. (2016). Update on 'what' and 'where' in spatial language: A new division of labor for spatial terms. *Cognitive Science*, in press.
Landau, B., & Hoffman, J. E. (2005). Parallels between spatial cognition and spatial language: Evidence from Williams syndrome. *Journal of Memory and Language*, *53*(2), 163-185.
Landau, B., & Jackendoff, R. (1993). "What" and "where" in spatial language and spatial cognition. *Behavioural and Brain Sciences*, *16*, 217-265.
Landau, B., Johannes, K., Skordos, D., & Papafragou, A. (2016). Containment and support: Core and complexity in spatial language learning. *Cognitive Science,* doi: 10.1111/cogs.12389.
Landau, B., & Zukowski, A. (2011). Objects, motions, and paths: Spatial language in children with Williams syndrome. *Developmental Neuropsychology, 23*(1&2), 105-137.
Lansing, A. E., Ivnik, R. J., Cullum, C. M., & Randolph, C. (1999). An empirically derived short form of the Boston Naming Test. *Archives of Clinical Neuropsychology, 14,* 481-487.
Lawrence, B., Myerson, J., & Hale, S. (1998). Differential decline of verbal and visuospatial processing speed across the adult life span. *Aging, Neuropsychology, and Cognition*, *5*(2), 129-146.
Laws, K. R., Duncan, A., & Gale, T. M. (2010). 'Normal'semantic–phonemic fluency discrepancy in Alzheimer's disease? A meta-analytic study. *Cortex*, *46*(5), 595-601.
Lehnung, M., Leplow, B., Friege, L., Herzog, A., & Ferstl, R. (1998). Development of spatial memory and spatial orientation in preschoolers and primary school children. *British Journal of Psychology, 89,* 463-480.
Leifer, B. P. (2003). Early diagnosis of Alzheimer's disease: clinical and economic benefits. *Journal of the American Geriatrics Society*, *51*(5s2).
Leplow, B., Lehnung, M., Pohl, J., Herzog, A., Ferstl, R., & Mehdorn, M. (2003). Navigational place learning in children and young adults as assessed with a standardized locomotor search task. *British Journal of Psychology*, *94*(3), 299-317.
Levine, B., Svoboda, E., Hay, J. F., Winocur, G., & Moscovitch, M. (2002). Aging and autobiographical memory: Dissociating episodic from semantic retrieval. *Psychology and Aging*, *17*(4), 677-689.
Levinson, S. C. (1996). Frames of reference and Molyneux's question: Crosslinguistic evidence. In P. Bloom, M.A. Peterson, L. Nadel, & M.F. Garrett (Eds.), *Language and space,* pp. 109-169. Cambridge, MA: MIT Press.
Levinson, S. C. (2003). *Space in language and cognition: Explorations in cognitive diversity.* Cambridge: Cambridge University Press.
Levinson, S. C., Kita, S., Haun, D. B. M., & Rasch, B. H. (2002). Returning the tables: Language affects spatial reasoning. *Cognition*, *84*(2), 155-188.
Lewczuk, P., Mroczko, B., Fagan, A., & Kornhuber, J. (2015). Biomarkers of Alzheimer's disease and mild cognitive impairment: A current perspective. *Advances in Medical Sciences*, *60*(1), 76-82.
Leyhe, T., Milian, M., Müller, S., Eschweiler, G. W., & Saur, R. (2009). The minute hand phenomenon in the Clock Test of patients with early Alzheimer disease. *Journal of Geriatric Psychiatry and Neurology*, *22*(2), 119-129.
Lezak, M. D., Howieson, D. B., Bigler, E. D., & Tranel, D. (2012). *Neuropsychological assessment* (5th ed.). New York: Oxford University Press.
Li, P., & Gleitman, L. (2002). Turning the tables: language and spatial reasoning. *Cognition, 83*(3), 265-294.

Liljeström, M., Tarkiainen, A., Parviainen, T., Kujala, J., Numminen, J., Hiltunen, J., Laine, M., & Salmelin, R. (2008). Perceiving and naming actions and objects. *NeuroImage, 41*(3), 1132-1141.
Lim, Y. Y., Maruff, P., Pietrzak, R. H., Ellis, K. A., Darby, D., Ames, D., & Savage, G. (2014). Aβ and cognitive change: Examining the preclinical and prodromal stages of Alzheimer's disease. *Alzheimer's & Dementia, 10*(6), 743-751.
Lim, Y.Y., Pietrzak, R.H., Bourgeat, P., Ames, D., Ellis, K.A., Rembach, A., Harrington, K., Salvado, O., Martins, R.N., Snyder, P.J., & Masters, C.L. (2015). Relationships between performance on the Cogstate Brief Battery, neurodegeneration, and Aβ accumulation in cognitively normal older adults and adults with MCI. *Archives of Clinical Neuropsychology*, *30*(1), 49-58.
Lin, C. Y., Chen, T. B., Lin, K. N., Yeh, Y. C., Chen, W. T., Wang, K. S., & Wang, P. N. (2014). Confrontation naming errors in Alzheimer's disease. *Dementia and Geriatric Cognitive Disorders*, *37*(1-2), 86-94.
Lin, M., Fwu, P. T., Buss, C., Davis, E. P., Head, K., Muftuler, L. T., Sandman, C. A., & Su, M. Y. (2013). Developmental changes in hippocampal shape among preadolescent children. *International Journal of Developmental Neuroscience, 31*, 473-481.
Lineweaver, T. T., Salmon, D. P., Bondi, M. W., & Corey-Bloom, J. (2005). Differential effects of Alzheimer's disease and Huntington's disease on the performance of mental rotation. *Journal of the International Neuropsychological Society*, *11*(1), 30-39.
Lithfous, S., Dufour, A., Blanc, F., & Després, O. (2014). Allocentric but not egocentric orientation is impaired during normal aging: An ERP study. *Neuropsychology, 28*(5), 761-771.
Lithfous, S., Dufour, A., & Després, O. (2013). Spatial navigation in normal aging and the prodromal stage of Alzheimer’s disease: Insights from imaging and behavioral studies. *Ageing Research Reviews*, *12*(1), 201-213.
Liu, C. C., Kanekiyo, T., Xu, H., & Bu, G. (2013). Apolipoprotein E and Alzheimer disease: Risk, mechanisms and therapy. *Nature Reviews Neurology, 9*(2), 106-118.
Liu, I., Levy, R. M., Barton, J. J. S., & Iaria, G. (2011). Age and gender differences in various topographical orientation strategies. *Brain Research*, *1410*, 112-119.
Logan, G. D., & Sadler, D. D. (1996). A computational analysis of the apprehension of spatial relations. In P. Bloom, M. A. Peterson, L. Nadel, & M. F. Garrett (Eds.), *Language and space* (pp. 493-529). Cambridge, MA: MIT Press.
Lövdén, M., Schaefer, S., Noack, H., Bodammer, N. C., Kühn, S., Heinze, H.-J., Düzel, E., Bäckman, L., & Lindenberger, U. (2012). Spatial navigation training protects the hippocampus against age-related changes during early and late adulthood. *Neurobiology of Aging*, *33*(3), 6209-62022.
Lu, L. H., Crosson, B., Nadeau, S. E., Heilman, K. M., Gonzalez-Rothi, L. J., Raymer, A., Gilmore, R. L., Bauer, R. M., & Roper, S. N. (2002). Category-specific naming deficits for objects and actions: Semantic attribute and grammatical role hypotheses. *Neuropsychologia*, *40*(9), 1608-1621.
Luine, V. N., Wallace, M. E., & Frankfurt, M. (2011). Age-related deficits in spatial memory and hippocampal spines in virgin, female Fischer 344 rats. *Current Gerontology and Geriatrics Research:*316386.
Lukatela, K., Malloy, P., Jenkins, M., & Cohen, R. (1998). The naming deficit in early Alzheimer’s and vascular dementia. *Neuropsychology, 12*, 565-572.
Luo, L., & Craik, F. I. (2008). Aging and memory: A cognitive approach. *The Canadian Journal of Psychiatry, 53*(6), 346-353.
Lustig, C., Snyder, A. Z., Bhakta, M., O'Brien, K. C., McAvoy, M., Raichle, M. E., & Buckner, R. L. (2003). Functional deactivations: Change with age and dementia of the Alzheimer type. *Proceedings of the National Academy of Sciences, 100*(24), 14504-14509.
Lutz, W., Sanderson, W., & Scherbov, S. (2008). The coming acceleration of global population ageing. *Nature*, *451*(7179), 716-719.

Luzzi, S., Pesallaccia, M., Fabi, K., Muti, M., Viticchi, G., Provinciali, L., & Piccirilli, M. (2011). Non-verbal memory measured by Rey–Osterrieth Complex Figure B: Normative data. *Neurological Sciences*, *32*(6), 1081-1089.
Mack, W. J., Freed, D. M., Williams, B. W., & Henderson, V. W. (1992). Boston Naming Test: Shortened versions for use in Alzheimer's disease. *Journal of Gerontology: Psychological Sciences, 47*, 154-158.
MacKay, A. J., Connor, L. T., Albert, M. L., & Obler, L. K. (2002). Noun and verb retrieval in healthy aging. *Journal of the International Neuropsychological Society, 8*(06), 764-770.
MacLeod, C. M. (1991). Half a century of research on the Stroop effect: An integrative review. *Psychological Bulletin*, *109*(2), 163-203.
Madden, D. J. (2007). Aging and visual attention. *Current directions in Psychological Science, 16*(2), 70-74.
Madden, D. J., Spaniol, J., Whiting, W. L., Bucur, B., Provenzale, J. M., Cabeza, R., White, L. E., & Huettel, S. A. (2007). Adult age differences in the functional neuroanatomy of visual attention: A combined fMRI and DTI study. *Neurobiology of Aging*, *28*(3), 459-476.
Maeda, Y., & Yoon, S. Y. (2013). A meta-analysis on gender differences in mental rotation ability measured by the Purdue spatial visualization tests: Visualization of rotations. *Educational Psychology Review*, *25*(1), 69-94.
Maestu, F., Arrazola, J., Fernandez, A., Simos, P.G., Amo, C., Gil-Gregorio, P., Fernandez, S., Papanicolaou, A., & Ortiz, T. (2003). Do cognitive patterns of brain magnetic activity correlate with hippocampal atrophy in Alzheimer's disease? *Journal of Neurology, Neurosurgery & Psychiatry*, *74*(2), 208-212.
Mahmood, O., Adamo, D., Briceno, E., & Moffat, S. D. (2009). Age differences in visual path integration. *Behavioural Brain Research*, *205*(1), 88-95.
Maguire, E. A., Burgess, N., & O'Keefe, J. (1999). Human spatial navigation: Cognitive maps, sexual dimorphism, and neural substrates. *Current Opinion in Neurobiology*, *9*(2), 171-177.
Majid, A., Bowerman, M., Kita, S., Haun, D. B., & Levinson, S. C. (2004). Can language restructure cognition? The case for space. *Trends in Cognitive Sciences*, *8*(3), 108-114.
Mammarella, I. C., Borella, E., Pastore, M., & Pazzaglia, F. (2013). The structure of visuospatial memory in adulthood. *Learning and Individual Differences*, *25*, 99-110.
Mapstone, M., Dickerson, K., & Duffy, C. J. (2008). Distinct mechanisms of impairment in cognitive ageing and Alzheimer's disease. *Brain*, *131*(6), 1618-1629.
March, E. G., Pattison, P., & Wales, R. (2009). The role of cognition in context-dependent language use: Evidence from Alzheimer's disease. *Journal of Neurolinguistics*, *22*(1), 18-36.
March, E. G., Wales, R., & Pattison, P. (2006). The uses of nouns and deixis in discourse production in Alzheimer's disease. *Journal of Neurolinguistics*, *19*(4), 311-340.
Marchette, S. A., Vass, L. K., Ryan, J., & Epstein, R. A. (2014). Anchoring the neural compass: coding of local spatial reference frames in human medial parietal lobe. *Nature Neuroscience*, *17*(11), 1598-1606.
Markostamou, I., Coventry, K., Fox, C., & McInnes, L. (2015). Both symbolic and embodied representations contribute to spatial language processing; Evidence from younger and older adults. *Proceedings of the 37th Annual Meeting of the Cognitive Science Society* (pp.1528-1523). Austin, TX: Cognitive Science Society.
Markostamou, I., Tsapkini, K., Karakostas, D., & Kosmidis, H. M. Verbal and design fluency in acute unilateral stroke: Implications for recovery. *Manuscript in preparation.*
Masterson, J., Druks, J., Kopelman, M., Clare, L., Garley, C., & Hayes, M. (2007). Selective naming (and comprehension) deficits in Alzheimer's disease? *Cortex*, *43*(7), 921-934.
Mathuranath, P. S., George, A., Cherian, P. J., Alexander, A. L., Sarma, S. G., & Sarma, P. S. (2003). Effects of age, education and gender on verbal fluency. *Journal of Clinical and Experimental Neuropsychology*, *25*(8), 1057-1064.

Matthews, F. E., Arthur, A., Barnes, L. E., Bond, J., Jagger, C., Robinson, L., & Medical Research Council Cognitive Function and Ageing Collaboration. (2013). A two-decade comparison of prevalence of dementia in individuals aged 65 years and older from three geographical areas of England: results of the Cognitive Function and Ageing Study I and II. *The Lancet*, *382*(9902), 1405-1412.

Mätzig, S., Druks, J., Masterson, J., & Vigliocco, G. (2009). Noun and verb differences in picture naming: Past studies and new evidence. *Cortex*, *45*(6), 738-758.

McCartney, K., Burchinal, M. R., & Bub, K. L. (2006). Best practices in quantitative methods for developmentalists. *Monographs of the Society for Research in Child Development*, *71*(3), 1-145.

McDaniel, M.A., & Einstein, G. O. (2011). The neuropsychology of prospective memory in normal aging: A componential approach. *Neuropsychologia*, *49*, 2147-2155.

McDonough, L., Choi, S., & Mandler, J. M. (2003). Understanding spatial relations: Flexible infants, lexical adults. *Cognitive Psychology*, *46*(3), 229-259.

McKhann, G. M., Knopman, D. S., Chertkow, H., Hyman, B. T., Jack, C. R., Kawas, C. H., Klunk, W. E., Koroshetz, W. J., Manly, J. J., Mayeux, R., & Mohs, R. C. (2011). The diagnosis of dementia due to Alzheimer’s disease: Recommendations from the National Institute on Aging-Alzheimer’s Association workgroups on diagnostic guidelines for Alzheimer's disease. *Alzheimer's & Dementia*, *7*(3), 263-269.

Meadmore, K. L., Dror, I. E., & Bucks, R. S. (2009). Lateralization of spatial processing and age. *Laterality*, *14*, 1-13.

Medina, J., Kannan, V., Pawlak, M. A., Kleinman, J. T., Newhart, M., Davis, C., Heidler-Gary, J. E., Herskovits, E. H., & Hillis, A. E., 2009. Neural substrates of visuospatial processing in distinct reference frames: Evidence from unilateral spatial neglect. *Journal of Cognitive Neuroscience*, *21*(11), 2073-2084.

Mendez, M. F., Clark, D. G., Shapira, J. S., & Cummings, J. L. (2003). Speech and language in progressive nonfluent aphasia compared with early Alzheimer’s disease. *Neurology*, *61*(8), 1108-1113.

Meulenbroek, O., Rijpkema, M., Kessels, R. P., Rikkert, M. G. O., & Fernández, G. (2010). Autobiographical memory retrieval in patients with Alzheimer's disease. *Neuroimage*, *53*(1), 331-340.

Michaelson, D. M. (2014). APOE ε4: The most prevalent yet understudied risk factor for Alzheimer's disease. *Alzheimer's & Dementia*, *10*(6), 861-868.

Miller, G. A., & Johnson-Laird, P. N. (1976). *Language and perception.* Cambridge, MA: Harvard University Press.

Mishra, R. C., Dasen, P. R., & Niraula, S. (2003). Ecology, language, and performance on spatial cognitive tasks. *International Journal of Psychology*, *38*(6), 366-383.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex “frontal lobe” tasks: A latent variable analysis. *Cognitive Psychology*, *41*(1), 49-100.

Moffat, S. D. (2009). Aging and spatial navigation: What do we know and where do we go? *Neuropsychology Review*, *19*(4), 478-489.

Moffat, S. D., Elkins, W., & Resnick, S. M. (2006). Age differences in the neural systems supporting human allocentric spatial navigation. *Neurobiology of Aging*, *27*(7), 965-972.

Moffat, S. D., Kennedy, K. M., Rodrigue, K. M., & Raz, N. (2007). Extrahippocampal contributions to age differences in human spatial navigation. *Cerebral Cortex*, *17*(6), 1274–1282.

Moffat, S. D., Zonderman, A. B., & Resnick, S. M. (2001). Age differences in spatial memory in a virtual environment navigation task. *Neurobiology of Aging*, *22*, 787-796.

Monacelli, A. M., Cushman, L. A., Kavcic, V., & Duffy, C. J. (2003). Spatial disorientation in Alzheimer’s disease: The remembrance of things passed. *Neurology*, *61*(11), 1491-1497.

Montello, D. R. (1993). Scale and multiple psychologies of space. In A. U. Frank & I. Campari (Eds.), *Spatial information theory: A theoretical basis for GIS (Lecture notes in computer science, 716),* pp. 312-321. Berlin: Springer-Verlag.
Moodley, K., Minati, L., Contarino, V., Prioni, S., Wood, R., Cooper, R., D'incerti, L., Tagliavini, F., & Chan, D. (2015). Diagnostic differentiation of mild cognitive impairment due to Alzheimer's disease using a hippocampus-dependent test of spatial memory. *Hippocampus*, *25*(8), 939-951.
Morganti, F., Stefanini, S., & Riva, G. (2013). From allo-to egocentric spatial ability in early Alzheimer’s disease: a study with virtual reality spatial tasks. *Cognitive Neuroscience*, *4*, 171-180.
Mormino, E. C. (2014). The relevance of beta-amyloid on markers of Alzheimer’s disease in clinically normal individuals and factors that influence these associations. *Neuropsychology Review*, *24*(3), 300-312.
Morris, M. C., & Tangney, C. C. (2014). Dietary fat composition and dementia risk. *Neurobiology of Aging*, *35*, S59-S64.
Mortensen, L., Meyer, A. S., & Humphreys, G. W. (2008). Speech planning during multiple-object naming: Effects of ageing. *The Quarterly Journal of Experimental Psychology*, *61*(8), 1217-1238.
Moseley, R. L., & Pulvermüller, F. (2014). Nouns, verbs, objects, actions, and abstractions: local fMRI activity indexes semantics, not lexical categories. *Brain and Language*, *132*, 28-42.
Mou, W., & McNamara, T. P. (2002). Intrinsic frames of reference in spatial memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 28*(1), 162.
Mungas, D., Harvey, D., Reed, B.R., Jagust, W.J., DeCarli, C., Beckett, L., Mack, W.J., Kramer, J.H., Weiner, M.W., Schuff, N., & Chui, H.C. (2005). Longitudinal volumetric MRI change and rate of cognitive decline. *Neurology*, *65*(4), 565-571.
Munnich, E., & Landau, B. (2010). Developmental decline in the acquisition of spatial language. *Language Learning and Development*, *6*(1), 32–59.
Munnich, E., Landau, B., & Dosher, B. A. (2001). Spatial language and spatial representation: A cross-linguistic comparison. *Cognition, 81*(3), 171-207.
Murphy, K. J., Rich, J. B., & Troyer, A. K. (2006). Verbal fluency patterns in amnestic mild cognitive impairment are characteristic of Alzheimer's type dementia. *Journal of the International Neuropsychological Society*, *12*(4), 570-574.
Murre, J. M., Janssen, S. M., Rouw, R., & Meeter, M. (2013). The rise and fall of immediate and delayed memory for verbal and visuospatial information from late childhood to late adulthood. *Acta Psychologica*, *142*(1), 96-107.
Myers, N., Pasquini, L., Göttler, J., Grimmer, T., Koch, K., Ortner, M., & Förstl, H. (2014). Within-patient correspondence of amyloid-β and intrinsic network connectivity in Alzheimer’s disease. *Brain*, *137*(7), 2052-2064.
Myerson, J., Emery, L., White, D. A., & Hale, S. (2003). Effects of age, domain, and processing demands on memory span: Evidence for differential decline. *Aging, Neuropsychology, and Cognition*, *10*(1), 20-27.
Myerson, J., Hale, S., Rhee, S. H., & Jenkins, L. (1999). Selective interference with verbal and spatial working memory in young and older adults. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, *54*(3), 161-164.
Nagel, I.E., Preuschhof, C., Li, S.C., Nyberg, L., Bäckman, L., Lindenberger, U., & Heekeren, H.R. (2009). Performance level modulates adult age differences in brain activation during spatial working memory. *Proceedings of the National Academy of Sciences*, *106*(52), 22552-22557.
Nardini, M., Burgess, N., Breckenridge, K., & Atkinson, J. (2006). Differential developmental trajectories for egocentric, environmental and intrinsic frames of reference in spatial memory. *Cognition*, *101*(1), 153-172.
Nasreddine, Z. S., Phillips, N. A., Bédirian, V., Charbonneau, S., Whitehead, V., Collin, I., Cummings, J. L., & Chertkow, H. (2005). The Montreal Cognitive Assessment, MoCA: A brief screening tool for mild cognitive impairment. *Journal of the American Geriatrics Society*, *53*(4), 695-699.

Nelson, P. T., Alafuzoff, I., Bigio, E. H., Bouras, C., Braak, H., Cairns, N. J., Davies, P., Tredici, K. D., & Duyckaerts, C. (2012). Correlation of Alzheimer disease neuropathologic changes with cognitive status: A review of the literature. *Journal of Neuropathology & Experimental Neurology*, *71*(5), 362-381.
Newman, M. C., & Kaszniak, A. W. (2010). Spatial memory and aging: Performance on a human analog of the Morris water maze. *Aging, Neuropsychology, and Cognition: A Journal on Normal and Dysfunctional Development, 7*(2), 37-41.
Ngandu, T., von Strauss, E., Helkala, E. L., Winblad, B., Nissinen, A., Tuomilehto, J., Soininen, H., & Kivipelto, M. (2007). Education and dementia - What lies behind the association? *Neurology*, *69*(14), 1442-1450.
Nicholas, M., Obler, L., Albert, M., & Goodglass, H. (1985). Lexical retrieval in healthy aging. *Cortex*, *21*(4), 595-606.
Nicholas, M., Obler, L. K., Au, R., & Albert, M. L. (1996). On the nature of naming errors in aging and dementia: A study of semantic relatedness. *Brain and Language*, *54*(2), 184-195.
Nitz, D. (2009). Parietal cortex, navigation, and the construction of arbitrary reference frames for spatial information. *Neurobiology of Learning and Memory*, *91*(2), 179-185.
Noordzij, M. L., Neggers, S, F. W., Ramsey, N. F., & Postma, A. (2008). Neural correlates of locative prepositions. *Neuropsychologia*, *46*, 1576-1580.
Noordzij, M. L., Van der Lubbe, R. H. J., Neggers, S. F. W., & Postma, A. (2004). Spatial tapping interferes with the processing of linguistic spatial relations. *Canadian Journal of Experimental Psychology*, *58*, 259-271.
Noordzij, M. L., Van der Lubbe, R. H., & Postma, A. (2005). Strategic and automatic components in the processing of linguistic spatial relations. *Acta Psychologica, 119*(1), 1-20.
Noordzij, M. L., Zuidhoek, S., & Postma, A. (2006). The influence of visual experience on the ability to form spatial mental models based on route and survey descriptions. *Cognition*, *100*(2), 321-342.
Nys, M., Gyselinck, V., Orriols, E., & Hickmann, M. (2014). Landmark and route knowledge in children’s spatial representation of a virtual environment. *Frontiers in Psychology, 5*:1522.
Oh, H., Madison, C., Villeneuve, S., Markley, C., & Jagust, W. J. (2013). Association of gray matter atrophy with age, β-amyloid, and cognition in aging. *Cerebral Cortex*, *24*(6), 1609-1618.
Oosterman, J. M., Vogels, R. L., van Harten, B., Gouw, A. A., Poggesi, A., Scheltens, P., Kessels, R. P., & Scherder, E. J. (2010). Assessing mental flexibility: Neuroanatomical and neuropsychological correlates of the Trail Making Test in elderly people. *The Clinical Neuropsychologist*, *24*(2), 203-219.
Orme, E. (2009). Identifying the functional architecture underlying multiple representations in visual working memory. Unpublished Doctoral Thesis, University of Northumbria, UK.
Osterrieth, P. A. (1944). Fe test de copie d’une figure complexe: Contribution a l’etude de la perception et de la memoire. *Archives de Psychologie, 30*, 286-356.
Packard, M. G., & McGaugh, J. L. (1996). Inactivation of hippocampus or caudate nucleus with lidocaine differentially affects expression of place and response learning. *Neurobiology of Learning and Memory, 65*(1), 65-72.
Pai, M. C., & Jacobs, W. J. (2004). Topographical disorientation in community-residing patients with Alzheimer's disease. *International Journal of Geriatric Psychiatry*, *19*(3), 250-255.
Park, D. C., Lautenschlager, G., Hedden, T., Davidson, N. S., Smith, A. D., & Smith, P. K. (2002). Models of visuospatial and verbal memory across the adult life span. *Psychology and Aging, 17,* 299-320.
Park, D. C., & Reuter-Lorenz, P. (2009). The adaptive brain: Aging and neurocognitive scaffolding. *Annual Review of Psychology*, *60*, 173-196.
Park, D. C., Welsh, R. C., Marshuetz, C., Gutchess, A. H., Mikels, J., Polk, T. A., et al. (2003). Working memory for complex scenes: Age differences in frontal and hippocampal activations. *Journal of Cognitive Neuroscience, 15*, 1122-1134.

Parra, M. A., Abrahams, S., Fabi, K., Logie, R., Luzzi, S., & Della Sala, S. (2009). Short-term memory binding deficits in Alzheimer's disease. *Brain*, *132*(4), 1057-1066.
Parra, M. A., Abrahams, S., Logie, R. H., Méndez, L. G., Lopera, F., & Della Sala, S. (2010). Visual short-term memory binding deficits in familial Alzheimer's disease. *Brain*, *133*(9), 2702-2713.
Partington, J. E., & Leiter, R. G. (1949). Partington's Pathways Test. *Psychological Service Center Journal*.
Patterson, K., Nestor, P. J., & Rogers, T. T. (2007). Where do you know what you know? The representation of semantic knowledge in the human brain. *Nature Reviews Neuroscience*, *8*(12), 976-987.
Paxton, J. L., Peavy, G. M., Jenkins, C., Rice, V. A., Heindel, W. C., & Salmon, D. P. (2007). Deterioration of visual-perceptual organization ability in Alzheimer's disease. *Cortex*, *43*(7), 967-975.
Peelle, J. E., Troiani, V., Wingfield, A., & Grossman, M. (2009). Neural processing during older adult' comprehension of spoken sentences: Age differences in resource allocation and connectivity. *Cerebral Cortex*: bhp142.
Peña-Casanova, J., Gramunt-Fombuena, N., Quiñones-Úbeda, S., Sánchez-Benavides, G., Aguilar, M., Badenes, D., Molinuevo, J. L., Robles, A., Barquero, M. S., Payno, M., & Antúnez, C. (2009). Spanish multicenter normative studies (NEURONORMA Project): Norms for the Rey-Osterrieth complex figure. *Archives of Clinical Neuropsychology*, p.acp041.
Peña-Casanova, J., Quiñones-Úbeda, S., Gramunt-Fombuena, N., Quintana-Aparicio, M., Aguilar, M., Badenes, D., Cerulla, N., Molinuevo, J. L., Ruiz, E., Robles, A., & Barquero, M. S. (2009). Spanish multicenter normative studies (NEURONORMA Project): Norms for verbal fluency tests. *Archives of Clinical Neuropsychology*: p.acp042.
Peña, D., Contreras, M. J., Shih, P. C., & Santacreu, J. (2008). Solution strategies as possible explanations of individual and sex differences in a dynamic spatial task. *Acta Psychologica*, *128*(1), 1-14.
Persson, J., Lustig, C., Nelson, J. K., & Reuter-Lorenz, P. A. (2007). Age differences in deactivation: a link to cognitive control? *Journal of Cognitive Neuroscience*, *19*(6), 1021-1032.
Peraita, H., Diaz, C., & Anllo-Vento, L. (2008). Processing of semantic relations in normal aging and Alzheimer's disease. *Archives of Clinical Neuropsychology*, *23*(1), 33-46.
Petrella, J. R., Sheldon, F. C., Prince, S. E., Calhoun, V. D., & Doraiswamy, P. M. (2011). Default mode network connectivity in stable vs progressive mild cognitive impairment. *Neurology*, *76*(6), 511-517.
Phillips, C. E., Jarrold, C., Baddeley, A. D., Grant, J., & Karmiloff-Smith, A. (2004). Comprehension of spatial language terms in Williams syndrome: Evidence for an interaction between domains of strength and weakness. *Cortex*, *40*(1), 85-101.
Phillips, R. (1979). Phillips S & M Rotation Test. Windsor, Berks: NFER-NELSON.
Phillips, W.A. (1983). Short-term visual memory. *Philosophical Transactions of the Royal Society of London, 302*, 295-309.
Piaget, J., & Inhelder, B. (1956). *Child's conception of space*. New York: Routledge.
Piatt, A. L., Fields, J. A., Paolo, A. M., Koller, W. C., & Tröster, A. I. (1999). Lexical, semantic, and action verbal fluency in Parkinson's disease with and without dementia. *Journal of Clinical and Experimental Neuropsychology*, *21*(4), 435-443.
Piefke, M., Onur, Ö. a, & Fink, G. R. (2012). Aging-related changes of neural mechanisms underlying visual-spatial working memory. *Neurobiology of Aging*, *33*(7), 1284-1297.
Pietrzak, R. H., Cohen, H., & Snyder, P. J. (2007). Spatial learning efficiency and error monitoring in normal aging: An investigation using a novel hidden maze learning test. *Archives of Clinical Neuropsychology*, *22*(2), 235-245.
Piolino, P., Desgranges, B., Benali, K., & Eustache, F. (2002). Episodic and semantic remote autobiographical memory in ageing. *Memory*, *10*(4), 239-257.

Postma, A., Kessels, R. P., & van Asselen, M. (2008). How the brain remembers and forgets where things are: The neurocognition of object–location memory. *Neuroscience & Biobehavioral Reviews*, *32*(8), 1339-1345.
Prince, M., Knapp, M., Guerchet, M., McCrone, P., Prina, M., Comas-Herrera, A., Wittenberg, R., Adelaja, B., Hu, B., King, D., & Rehill, A. (2014). Dementia UK: Update. *Alzheimer's Society*.
Pruden, S. M., Levine, S. C., & Huttenlocher, J. (2011). Children's spatial thinking: Does talk about the spatial world matter? *Developmental Science*, *14*(6), 1417-1430.
Pulvermüller, F. (2012). Meaning and the brain: The neurosemantics of referential, interactive, and combinational knowledge. *Journal of Neurolinguistics*, *25*(5), 423-459.
Purser, H. R., Farran, E. K., Courbois, Y., Lemahieu, A., Mellier, D., Sockeel, P., & Blades, M. (2012). Short-term memory, executive control, and children's route learning. *Journal of Experimental Child Psychology*, *113*(2), 273-285.
Quental, N. B. M., Brucki, S. M. D., & Bueno, O. F. A. (2013). Visuospatial function in early Alzheimer's disease—the use of the Visual Object and Space Perception (VOSP) battery. *PLoS One*, *8*(7): e68398.
Rabbitt, P. M. A., McInnes, L., Diggle, P., Holland, F., Bent, N., Abson, V., & Horan, M. (2004). The University of Manchester longitudinal study of cognition in normal healthy old age, 1983 through 2003. *Aging Neuropsychology and Cognition*, *11*(2-3), 245-279.
Ralph, M. L., McClelland, J. L., Patterson, K., Galton, C. J., & Hodges, J. R. (2001). No right to speak? The relationship between object naming and semantic impairment: Neuropsychological evidence and a computational model. *Journal of Cognitive Neuroscience*, *13*(3), 341-356.
Ramanan, S., de Souza, L. C., Moreau, N., Sarazin, M., Teixeira, A. L., Allen, Z., Guimarães, H. C., Caramelli, P., Dubois, B., Hornberger, M., & Bertoux, M. (2017). Determinants of theory of mind performance in Alzheimer's disease: A data-mining study. *Cortex*, *88*, 8-18.
Rami, L., Sala-Llonch, R., Solé-Padullés, C., Fortea, J., Olives, J., Lladó, A., Peña-Gómez, C., Balasa, M., Bosch, B., Antonell, A., & Sanchez-Valle, R. (2012). Distinct functional activity of the precuneus and posterior cingulate cortex during encoding in the preclinical stage of Alzheimer's disease. *Journal of Alzheimer's Disease*, *31*(3), 517-526.
Rankin, K. P., Mucke, L., Miller, B. L., & Gorno-Tempini, M. L. (2007). Spatial cognition and the human navigation network in AD and MCI. *Neurology*, *69*(10), 986-997.
Rao, H., Zhou, T., Zhuo, Y., Fan, S., & Chen, L. (2003). Spatiotemporal activation of the two visual pathways in form discrimination and spatial location: A brain mapping study. *Human Brain Mapping*, *18*(2), 79-89.
Raoux, N., Amieva, H., Le Goff, M., Auriacombe, S., Carcaillon, L., Letenneur, L., & Dartigues, J. F. (2008). Clustering and switching processes in semantic verbal fluency in the course of Alzheimer's disease subjects: Results from the PAQUID longitudinal study. *Cortex*, *44*(9), 1188-1196.
Raven, J. C. (1943). *The Mill Hill vocabulary scale*. London: H. K. Lewis & Co. Ltd.
Raven, J. C., & John Hugh Court. (1998). *Raven's progressive matrices and vocabulary scales*. Oxford, UK: Oxford Psychologists Press.
Raz, N., Ghisletta, P., Rodrigue, K. M., Kennedy, K. M., & Lindenberger, U. (2010). Trajectories of brain aging in middle-aged and older adults: Regional and individual differences. *NeuroImage*, *51*(2), 501-511.
Raz, N., & Rodrigue, K. M. (2006). Differential aging of the brain: Patterns, cognitive correlates and modifiers. *Neuroscience & Biobehavioral Reviews*, *30*(6), 730-748.
Regier, T., & Zheng, M. (2007). Attention to endpoints: A cross-linguistic constraint on spatial meaning. *Cognitive Science*, *31*(4), 705-719.
Rémy, F., Mirrashed, F., Campbell, B., & Richter, W. (2005). Verbal episodic memory impairment in Alzheimer's disease: a combined structural and functional MRI study. *Neuroimage*, *25*(1), 253-266.
Reuter-Lorenz, P. A., & Cappell, K. A. (2008). Neurocognitive aging and the compensation hypothesis. *Current Directions in Psychological Science*, *17*, 177-182.

Reuter-Lorenz, P. A., Jonides, J., Smith, E. E., Hartley, A., Miller, A., Marshuetz, C., & Koeppe, R. A. (2000). Age differences in the frontal lateralization of verbal and spatial working memory revealed by PET. *Journal of Cognitive Neuroscience*, *12*(1), 174-187.
Reuter-Lorenz, P. A., & Park, D. C. (2010). Human neuroscience and the aging mind: A new look at old problems. *The Journal of Gerontology: Psychological Sciences*, 10.1093/geronb/gbq035.
Reuter-Lorenz, P. A., & Park, D. C. (2014). How does it STAC up? Revisiting the scaffolding theory of aging and cognition. *Neuropsychology Review*, *24*(3), 355-370.
Ribordy, F., Jabès, A., Lavenex, P. B., & Lavenex, P. (2013). Development of allocentric spatial memory abilities in children from 18 months to 5 years of age. *Cognitive Psychology*, *66*(1), 1-29.
Riby, L. M., & Orme, E. (2013). A familiar pattern? Semantic memory contributes to the enhancement of visuo-spatial memories. *Brain and Cognition, 81*, 215-222.
Ritchie, K., Carrière, I., Su, L., O'Brien, J. T., Lovestone, S., Wells, K., & Ritchie, C. W. (2017). The midlife cognitive profiles of adults at high risk of late-onset Alzheimer's disease: The PREVENT study. *Alzheimer's & Dementia*, in press.
Robbins, T. W., James, M., Owen, A. M., Sahakian, B. J., Lawrence, A. D., McInnes, L., & RABBITT, P. M. (1998). A study of performance on tests from the CANTAB battery sensitive to frontal lobe dysfunction in a large sample of normal volunteers: Implications for theories of executive functioning and cognitive aging. *Journal of the International Neuropsychological Society*, *4*(05), 474-490.
Robinson, G., Rossor, M., & Cipolotti, L. (1999). Selective sparing of verb naming in a case of severe Alzheimer's disease. *Cortex*, *35*(3), 443-450.
Rodgers, M. K., Sindone, J. A. S., & Moffat, S. D. (2012). Effects of age on navigation strategy. *Neurobiology of Aging*, *33*(1), 202.e15-202.e22.
Rodriguez-Aranda, C., & Martinussen, M. (2006). Age-related differences in performance of phonemic verbal fluency measured by Controlled Oral Word Association Task (COWAT): A meta-analytic study. *Developmental Neuropsychology*, *30*(2), 697-717.
Rogers, S. L., & Friedman, R. B. (2008). The underlying mechanisms of semantic memory loss in Alzheimer's disease and semantic dementia. *Neuropsychologia*, *46*(1), 12-21.
Rogers, T. T., Ivanoiu, A., Patterson, K., & Hodges, J. R. (2006). Semantic memory in Alzheimer's disease and the frontotemporal dementias: a longitudinal study of 236 patients. *Neuropsychology*, *20*(3), 319.
Rombouts, S. A., Barkhof, F., Goekoop, R., Stam, C. J., & Scheltens, P. (2005). Altered resting state networks in mild cognitive impairment and mild Alzheimer's disease: An fMRI study. *Human Brain Mapping*, *26*(4), 231-239.
Rönnlund, M., Nyberg, L., Bäckman, L., & Nilsson, L. G. (2005). Stability, growth, and decline in adult life span development of declarative memory: Cross-sectional and longitudinal data from a population-based study. *Psychology and Aging*, *20*(1), 3-18.
Rosenbaum, R. S., Winocur, G., Binns, M. A., & Moscovitch, M. (2012). Remote spatial memory in aging: All is not lost. *Frontiers in Aging Neuroscience*, *4*, 1–10.
Rosenzweig, E. S., & Barnes, C. A. (2003). Impact of aging on hippocampal function: Plasticity, network dynamics, and cognition. *Progress in Neurobiology*, *69*, 143–179.
Ruby, P., Collette, F., D'Argembeau, A., Péters, F., Degueldre, C., Balteau, E., & Salmon, E. (2009). Perspective taking to assess self-personality: What's modified in Alzheimer's disease? *Neurobiology of Aging*, *30*(10), 1637-1651.
Ruggiero, G., D'Errico, O., & Iachini, T. (2016). Development of egocentric and allocentric spatial representations from childhood to elderly age. *Psychological Research*, *80*(2), 259-272.
Ryu, S. Y., Kwon, M. J., Lee, S. B., Yang, D. W., Kim, T. W., Song, I. U., Yang, P. S., Kim, H. J., & Lee, A. Y. (2010). Measurement of precuneal and hippocampal volumes using magnetic resonance volumetry in Alzheimer's disease. *Journal of Clinical Neurology*, *6*(4), 196-203.

Saccuman, M. C., Cappa, S. F., Bates, E. A., Arevalo, A., Della Rosa, P., Danna, M., & Perani, D. (2006). The impact of semantic reference on word class: An fMRI study of action and object naming. *NeuroImage*, *32*(4), 1865-1878.
Saccuzzo, D. P., Craig, A. S., Johnson, N. E., & Larson, G. E. (1996). Gender differences in dynamic spatial abilities. *Personality and Individual Differences*, *21*(4), 599-607.
Sadek, J. R., Johnson, S. A., White, D. A., Salmon, D. P., Taylor, K. I., DeLaPena, J. H., Paulsen, J. S., Heaton, R. K. & Grant, I. (2004). Retrograde amnesia in dementia: Comparison of HIV-associated dementia, Alzheimer's disease, and Huntington's disease. *Neuropsychology, 18*(4), 692-699.
Sagar, H. J., Cohen, N. J., Sullivan, E. V., Corkin, S., & Growdon, J. H. (1998). Remote memory function in Alzheimer's disease and Parkinson's disease. *Brain*, *111*(1), 185-206.
Sahyoun, C. P., Belliveau, J. W., Soulières, I., Schwartz, S., & Mody, M. (2010). Neuroimaging of the functional and structural networks underlying visuospatial vs. linguistic reasoning in high-functioning autism. *Neuropsychologia*, *48*(1), 86-95.
Salmon, D. P., & Bondi, M. W. (2009). Neuropsychological assessment of dementia. *Annual Review of Psychology*, *60*, 257-282.
Salthouse, T. A. (1995). Differential age-related influences on memory for verbal-symbolic information and visual-spatial information? *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, *50*(4), 193-201.
Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. *Psychological Review, 103*, 403–428.
Salthouse, T. A. (2000). Aging and measures of processing speed. *Biological Psychology*, *54*, 35-54.
Salthouse, T. A., Babcock, R. L., Skovronek, E., Mitchell, D. R., & Palmon, R. (1990). Age and experience effects in spatial visualization. *Developmental Psychology*, *26*(1), 128-136.
Sander, M. C., Lindenberger, U., & Werkle-Bergner, M. (2012). Lifespan age differences in working memory: A two-component framework. *Neuroscience & Biobehavioral Reviews*, *36*(9), 2007-2033.
Saucier, D. M., Green, S. M., Leason, J., MacFadden, A., Bell, S., & Elias, L. J. (2002). Are sex differences in navigation caused by sexually dimorphic strategies or by differences in the ability to use the strategies? *Behavioral Neuroscience*, *116*(3), 403-410.
Schmid, N. S., Taylor, K. I., Foldi, N. S., Berres, M., & Monsch, A. U. (2013). Neuropsychological signs of Alzheimer's disease 8 years prior to diagnosis. *Journal of Alzheimer's Disease*, *34*(2), 537-546.
Schmitter-Edgecombe, M., Vesneski, M., & Jones, D. W. R. (2000). Aging and word-finding: A comparison of spontaneous and constrained naming tests. *Archives of Clinical Neuropsychology, 15*(6), 479-493.
Schneider-Garces, N.J., Gordon, B.A., Brumback-Peltz, C.R., Shin, E., Lee, Y., Sutton, B.P., Maclin, E.L., Gratton, G., & Fabiani, M. (2010). Span, CRUNCH, and beyond: Working memory capacity and the aging brain. *Journal of Cognitive Neuroscience*, *22*(4), 655-669.
Schwindt, G. C., & Black, S. E. (2009). Functional imaging studies of episodic memory in Alzheimer's disease: A quantitative meta-analysis. *Neuroimage*, *45*(1), 181-190.
Serino, S., Cipresso, P., Morganti, F., & Riva, G. (2014). The role of egocentric and allocentric abilities in Alzheimer's disease: A systematic review. *Ageing Research Reviews*, *16*, 32-44.
Serino, S., Morganti, F., Di Stefano, F., & Riva, G. (2015). Detecting early egocentric and allocentric impairments deficits in Alzheimer's disease: An experimental study with virtual reality. *Frontiers in Aging Neuroscience*, *7*: 88.
Serino, S., & Riva, G. (2013). Getting lost in Alzheimer's disease: A break in the mental frame syncing. *Medical Hypotheses, 80*, 416-421.
Serra, L., Fadda, L., Perri, R., Caltagirone, C., & Carlesimo, G. A. (2010). The closing-in phenomenon in the drawing performance of Alzheimer's disease patients: A compensation account. *Cortex, 46*(8), 1031-1036.

Shafto, M. A., Burke, D. M., Stamatakis, E. A., Tam, P. P., & Tyler, L. K. (2007). On the tip-of-the-tongue: Neural correlates of increased word-finding failures in normal aging. *Journal of Cognitive Neuroscience*, *19*(12), 2060-2070.

Shafto, M. A., & Tyler, L. K. (2014). Language in the aging brain: The network dynamics of cognitive decline and preservation. *Science, 346*(6209), 583-587.

Shapiro, K., & Caramazza, A. (2003). Grammatical processing of nouns and verbs in left frontal cortex? *Neuropsychologia*, *41*(9), 1189-1198.

Shao, Z., Roelofs, A., & Meyer, A. S. (2012). Sources of individual differences in the speed of naming objects and actions: The contribution of executive control. *The Quarterly Journal of Experimental Psychology*, *65*(10), 1927-1944.

Shelton, A. L., & McNamara, T. P. (2001). Systems of spatial reference in human memory. *Cognitive Psychology*, *43*(4), 274-310.

Shepard, R. N., & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science, 171*, 701-703.

Shi, F., Liu, B., Zhou, Y., Yu, C., & Jiang, T. (2009). Hippocampal volume and asymmetry in mild cognitive impairment and Alzheimer's disease: Meta-analyses of MRI studies. *Hippocampus, 19*(11), 1055-1064.

Silverman, I., Choi, J., & Peters, M. (2007). The hunter-gatherer theory of sex differences in spatial abilities: Data from 40 countries. *Archives of Sexual Behavior*, *36*(2), 261-268.

Simard, M., van Reekum, R., & Myran, D. (2003). Visuospatial impairment in dementia with Lewy bodies and Alzheimer's disease: A process analysis approach. *International Journal of Geriatric Psychiatry*, *18*(5), 387-391.

Simmons, W. K., & Martin, A. (2009). The anterior temporal lobes and the functional architecture of semantic memory. *Journal of the International Neuropsychological Society*, *15*(05), 645-649.

Slobin, D. I. (1985). Crosslinguistic evidence for the language-making capacity. In Slobin, D. I. (Ed.), *The crosslinguistic study of language acquisition: Vol. 2. Theoretical issues* (pp. 1157-1256). Hillsdale: Erlbaum.

Snyder, P. J., Kahle-Wrobleski, K., Brannan, S., Miller, D. S., Schindler, R. J., DeSanti, S., & Caselli, R. J. (2014). Assessing cognition and function in Alzheimer's disease clinical trials: Do we have the right tools? *Alzheimer's & Dementia*, *10*(6), 853-860.

Sörös, P., Cornelissen, K., Laine, M., & Salmelin, R. (2003). Naming actions and objects: cortical dynamics in healthy adults and in an anomic patient with a dissociation in action/object naming. *Neuroimage*, *19*(4), 1787-1801.

Sperling, R. A., Dickerson, B. C., Pihlajamaki, M., Vannini, P., LaViolette, P. S., Vitolo, O. V., Hedden, T., Becker, J. A., Rentz, D. M., Selkoe, D. J., & Johnson, K. A. (2010). Functional alterations in memory networks in early Alzheimer’s disease. *Neuromolecular Medicine*, *12*(1), 27-43.

Squire, L. R., & Alvarez, P. (1995). Retrograde amnesia and memory consolidation: A neurobiological perspective. *Current Opinion in Neurobiology*, *5*(2), 169-177.

Stern, Y. (2002). What is cognitive reserve? Theory and research application of the reserve concept. *Journal of the International Neuropsychological Society*, *8*(03), 448-460.

Stern, Y. (2009). Cognitive reserve. *Neuropsychologia*, *47*(10), 2015-2028.

Stern, Y. (2012). Cognitive reserve in ageing and Alzheimer's disease. *The Lancet Neurology*, *11*(11), 1006-1012.

Stern, Y., Habeck, C., Moeller, J., Scarmeas, N., Anderson, K. E., Hilton, H. J., Flynn, J., Sackeim, H., & Van Heertum, R. (2005). Brain networks associated with cognitive reserve in healthy young and old adults. *Cerebral Cortex*, *15*, 394-402.

Störmer, V. S., Li, S. C., Heekeren, H. R., & Lindenberger, U. (2013). Normal aging delays and compromises early multifocal visual attention during object tracking. *Journal of Cognitive Neuroscience*, *25*(2), 188-202.

Strauss, E., Sherman, E. M., & Spreen, O. (2006). *A compendium of neuropsychological tests: Administration, norms, and commentary*. Oxford: Oxford University Press.

Stricker, N. H., Dodge, H. H., Dowling, N. M., Han, S. D., Erosheva, E. A., Jagust, W. J., & Alzheimer's Disease Neuroimaging Initiative. (2012). CSF biomarker associations with change in hippocampal volume and precuneus thickness: Implications for the Alzheimer's pathological cascade. *Brain imaging and behavior*, *6*(4), 599-609.

Struiksma, M. E., Noordzij, M. L., & Postma, A. (2009). What is the link between language and spatial images? Behavioral and neural findings in blind and sighted individuals. *Acta Psychologica*, *132*(2), 145-156.

Struiksma, M. E., & Postma, A. (2017). Tell me where to go: On the language of space. In A. Postma & I. J. M. van der Ham (Eds.), *Neuropsychology of Space: Spatial functions of the human brain* (pp. 197-230). London: Academic Press.

Stuss, D. T., & Alexander, M. P. (2000). Executive functions and the frontal lobes: A conceptual view. *Psychological Research, 63*, 289-298.

Spence, I., & Feng, J. (2010). Video games and spatial cognition. *Review of General Psychology, 14*(2), 92-104.

Sperling, R.A., Aisen, P.S., Beckett, L.A., Bennett, D.A., Craft, S., Fagan, A.M., Iwatsubo, T., Jack, C.R., Kaye, J., Montine, T.J., & Park, D.C. (2011). Toward defining the preclinical stages of Alzheimer's disease: Recommendations from the National Institute on Aging-Alzheimer's Association workgroups on diagnostic guidelines for Alzheimer's disease. *Alzheimer's & Dementia*, *7*(3), 280-292.

Sperling, R. A., Bates, J. F., Chua, E. F., Cocchiarella, A. J., Rentz, D. M., Rosen, B. R., Schacter, D. L., & Albert, M. S. (2003). fMRI studies of associative encoding in young and elderly controls and mild Alzheimer's disease. *Journal of Neurology, Neurosurgery & Psychiatry, 74*(1), 44-50.

Sperling, R., Mormino, E., & Johnson, K. (2014). The evolution of preclinical Alzheimer's disease: Implications for prevention trials. *Neuron*, *84*(3), 608-622.

Spintzer, R. L., Kroenke, K., Williams, J. B. W., & Löwe, B. (2006). A brief measure for assessing generalized anxiety disorder: the GAD-7. *Archives of Internal Medicine, 166*, 1092-1097.

Sullivan, E. V., Rohlfing, T., & Pfefferbaum, A. (2010). Quantitative fiber tracking of lateral and interhemispheric white matter systems in normal aging: Relations to timed performance. *Neurobiology of Aging*, *31*(3), 464-481.

Supekar, K., Menon, V., Rubin, D., Musen, M., & Greicius, M. D. (2008). Network analysis of intrinsic functional brain connectivity in Alzheimer's disease. *PLoS Computational Biology*, *4*(6): e1000100.

Szatloczki, G., Hoffmann, I., Vincze, V., Kalman, J., & Pakaski, M. (2015). Speaking in Alzheimer's disease, is that an early sign? Importance of changes in language abilities in Alzheimer's disease. *Frontiers in Aging Neuroscience, 7*: 195.

Tabachnick, B. G., & Fidell, L. S. (2001). *Using multivariate statistics* (5th ed.). New York: Pearson.

Taler, V., & Phillips, N. A. (2008). Language performance in Alzheimer's disease and mild cognitive impairment: A comparative review. *Journal of Clinical and Experimental Neuropsychology*, *30*(5), 501-556.

Tallberg, I. M., Ivachova, E., Tinchag, K. J., & Ostberg, P. (2008). Swedish norms for word fluency tests: FAS, animals and verbs. *Scandinavian Journal of Psychology, 49*, 479-485.

Tarampi, M. R., Heydari, N., & Hegarty, M. (2016). A tale of two types of perspective taking sex differences in spatial ability. *Psychological Science*, *27*(11), 1507-1516.

Techentin, C., Voyer, D., & Voyer, S. D. (2014). Spatial abilities and aging: A meta-analysis. *Experimental Aging Research*, *40*(4), 395-425.

Terry, D. P., Sabatinelli, D., Puente, A. N., Lazar, N. A., & Miller, L. S. (2015). A meta-analysis of fMRI activation differences during episodic memory in Alzheimer's disease and mild cognitive impairment. *Journal of Neuroimaging*, *25*(6), 849-860.

Tierney, M. C., Yao, C., Kiss, A., & McDowell, I. (2005). Neuropsychological tests accurately predict incident Alzheimer disease after 5 and 10 years. *Neurology*, *64*(11), 1853-1859.

Thal, D. R., Attems, J., & Ewers, M. (2014). Spreading of amyloid, tau, and microvascular pathology in Alzheimer's disease: Findings from neuropathological and neuroimaging studies. *Journal of Alzheimer's Disease*, *42*(s4), S421-S429.

Thiyagesh, S. N., Farrow, T. F., Parks, R. W., Accosta-Mesa, H., Young, C., Wilkinson, I. D., Hunter, M. D., & Woodruff, P. W. (2009). The neural basis of visuospatial perception in Alzheimer's disease and healthy elderly comparison subjects: an fMRI study. *Psychiatry Research: Neuroimaging*, *172*(2), 109-116.

Thomsen, T., Hugdahl, K., Ersland, L., Barndon, R., Lundervold, A., Smievoll, A.I., Roscher, B.E., & Sundberg, H. (2000). Functional magnetic resonance imaging (fMRI) study of sex differences in a mental rotation task. *Medical Science Monitor*, *6*(6), 1186-1196.

Thornton, R., & Light, L. L. (2006). Language comprehension and production in normal aging. In Birren, J. E., & Schaie, K. W. (Eds.), *Handbook of the psychology of aging.* London, Elsevier Academic Press.

Thornton, W. J. L., & Raz, N. (2006). Aging and the role of working memory resources in visuospatial attention. *Aging, Neuropsychology, and Cognition, 13,* 36-61.

Tombaugh, T. N. (2004). Trail Making Test A and B: normative data stratified by age and education. *Archives of Clinical Neuropsychology*, *19*(2), 203-214.

Tombaugh, T. N., Kozak, J., & Rees, L. (1999). Normative data stratified by age and education for two measures of verbal fluency: FAS and animal naming. *Archives of Clinical Neuropsychology, 14*(2), 167-177.

Tranel, D., Adolphs, R., Damasio, H., & Damasio, A. R. (2001). A neural basis for the retrieval of words for actions. *Cognitive Neuropsychology*, *18*(7), 655-674.

Tranel, D., & Kemmerer, D. (2004). Neuroanatomical correlates of locative prepositions. *Cognitive Neuropsychology, 21*, 719-749.

Tromp, D., Dufour, A., Lithfous, S., Pebayle, T., & Després, O. (2015). Episodic memory in normal aging and Alzheimer disease: Insights from imaging and behavioral studies. *Ageing Research Reviews*, *24*, 232-262.

Troyer, A. K. (2000). Normative data for clustering and switching on verbal fluency tasks. *Journal of Clinical and Experimental Neuropsychology*, *22*(3), 370-378.

Troyer, A. K., Moscovitch, M., Winocur, G., Alexander, M. P., & Stuss, D. (1998). Clustering and switching on verbal fluency: The effects of focal frontal- and temporal-lobe lesions. *Neuropsychologia*, *36*(6), 499-504.

Tsang, H. L., & Lee, T. M. C. (2003). The effect of ageing on confrontational naming ability. *Archives of Clinical Neuropsychology*, *18,* 81-89.

Tsantali, E., Economidis, D., & Tsolaki, M. (2013). Could language deficits really differentiate Mild Cognitive Impairment (MCI) from mild Alzheimer's disease? *Archives of Gerontology and Geriatrics*, *57*(3), 263-270.

Tu, S., Spiers, H. J., Hodges, J. R., Piguet, O., & Hornberger, M. (2017). Egocentric versus Allocentric Spatial Memory in Behavioral Variant Frontotemporal Dementia and Alzheimer’s Disease. *Journal of Alzheimer's Disease*, in press.

Tu, S., Wong, S., Hodges, J. R., Irish, M., Piguet, O., & Hornberger, M. (2015). Lost in spatial translation–A novel tool to objectively assess spatial disorientation in Alzheimer's disease and frontotemporal dementia. *Cortex*, *67*, 83-94.

Tubi, N., & Calev, A. (1989). Verbal and visuospatial recall by younger and older subjects: use of matched tasks. *Psychology and Aging*, *4*(4), 493-495.

Turner, G. R., & Spreng, R. N. (2012). Executive functions and neurocognitive aging: dissociable patterns of brain activity. *Neurobiology of Aging*, *33*(4), 826e1-826.e13.

Tyler, L. K., Russell, R., Fadili, J., & Moss, H. E. (2001). The neural representation of nouns and verbs: PET studies. *Brain*, *124*(8), 1619-1634.
Uematsu, A., Matsui, M., Tanaka, C., Takahashi, T., Noguchi, K., Suzuki, M., & Nishijo, H. (2012). Developmental trajectories of amygdala and hippocampus from infancy to early adulthood in healthy individuals. *PloS one*, *7*(10), e46970.
Ungerleider, L. G., & Mishkin, M. (1982). Two cortical visual systems. (pp. 549-586). In: Ingle, D. J., Goodale, M. A., & Mansfield, R. J. W. (Eds.). *Analysis of visual behavior*. Cambridge, MA: MIT Press.
United Nations, Department of Economic and Social Affairs, Population Division (2013). *World population ageing 2013*. New York: United Nations publication, ST/ESA/SER.A/348.
Valls-Pedret, C., Sala-Vila, A., Serra-Mir, M., Corella, D., de la Torre, R., Martínez-González, M.Á., Martínez-Lapiscina, E.H., Fitó, M., Pérez-Heras, A., Salas-Salvadó, J., & Estruch, R. (2015). Mediterranean diet and age-related cognitive decline: A randomized clinical trial. *JAMA Internal Medicine*, *175*(7), 1094-1103.
Van Boxtel, M. P. J., Ten Tusscher, M. P. M., Metsemakers, J. F. M., Willems, B., & Jolles, J. (2001). Visual determinants of reduced performance on the Stroop Color-Word Test in normal aging individuals. *Journal of Clinical and Experimental Neuropsychology*, *23*, 620-627.
Van Der Elst, W., Van Boxtel, M. P., Van Breukelen, G. J., & Jolles, J. (2006). Normative data for the Animal, Profession and Letter M Naming verbal fluency tests for Dutch speaking participants and the effects of age, education, and sex. *Journal of the International Neuropsychological Society*, *12*(01), 80-89.
van der Ham, I. J., & Postma, A. (2010). Lateralization of spatial categories: A comparison of verbal and visuospatial categorical relations. *Memory & Cognition*, *38*(5), 582-590.
Vann, S. D., Aggleton, J. P., & Maguire, E. A. (2009). What does the retrosplenial cortex do? *Nature Reviews Neuroscience*, *10*(11), 792-802.
Vasilyeva, M., & Lourenco, S. F. (2012). Development of spatial cognition. *Wiley Interdisciplinary Reviews: Cognitive Science*, *3*(3), 349-362.
Vecchi, T., Richardson, J., & Cavallini, E. (2005). Passive storage versus active processing in working memory: Evidence from age-related variations in performance. *European Journal of Cognitive Psychology*, *17*(4), 521-539.
Verhaeghen, P. (2003). Aging and vocabulary score: A meta-analysis. *Psychology and Aging*, *18*(2), 332-339.
Verma, M., & Howard, R. J. (2012). Semantic memory and language dysfunction in early Alzheimer's disease: A review. *International Journal of Geriatric Psychiatry*, *27*(12), 1209-1217.
Vigliocco, G., Vinson, D. P., Druks, J., Barber, H., & Cappa, S. F. (2011). Nouns and verbs in the brain: A review of behavioural, electrophysiological, neuropsychological and imaging studies. *Neuroscience & Biobehavioral Reviews*, *35*(3), 407-426.
Vigliocco, G., Warren, J., Siri, S., Arciuli, J., Scott, S., & Wise, R. (2006). The role of semantics and grammatical class in the neural representation of words. *Cerebral Cortex*, *16*(12), 1790-1796.
Vik, P. W., Cellucci, T., Jarchow, A., & Hedt, J. (2004). Cognitive impairment in substance abuse. *Psychiatric Clinics of North America*, *27*(1), 97-109.
Villemagne, V. L., Burnham, S., Bourgeat, P., Brown, B., Ellis, K. A., Salvado, O., & Ames, D. (2013). Amyloid β deposition, neurodegeneration, and cognitive decline in sporadic Alzheimer's disease: A prospective cohort study. *The Lancet Neurology*, *12*(4), 357-367.
Viskontas, I. V., Holyoak, K. J., & Knowlton, B. J. (2005). Relational integration in older adults. *Thinking & Reasoning*, *11*(4), 390-410.
Viskontas, I. V., Morrison, R. G., Holyoak, K. J., Hummel, J. E., & Knowlton, B. J. (2004). Relational integration, inhibition, and analogical reasoning in older adults. *Psychology and Aging*, *19*(4), 581-591.

Visser, M., Jefferies, E., & Ralph, M. L. (2010). Semantic processing in the anterior temporal lobes: A meta-analysis of the functional neuroimaging literature. *Journal of Cognitive Neuroscience*, *22*(6), 1083-1094.

Vlček, K., & Laczó, J. (2014). Neural correlates of spatial navigation changes in mild cognitive impairment and Alzheimer's disease. *Frontiers in Behavioral Neuroscience*, *8*: 89.

Voss, M.W., Erickson, K.I., Chaddock, L., Prakash, R.S., Colcombe, S.J., Morris, K.S., Doerksen, S., Hu, L., McAuley, E., & Kramer, A.F. (2008). Dedifferentiation in the visual cortex: An fMRI investigation of individual differences in older adults. *Brain Research*, *1244*, 121-131.

Wallentin, M., Østergaard, S., Lund, T. E., Østergaard, L., & Roepstorff, A. (2005). Concrete spatial language: See what I mean? *Brain and Language*, *92*, 221-233.

Wallentin, M., Roepstorff, A., Glover, R., & Burgess, N. (2006). Parallel memory systems for talking about location and age in precuneus, caudate and Broca's region. *Neuroimage*, *32*(4), 1850-1864.

Wallentin, M., Weed, E., Østergaard, L., Mouridsen, K., & Roepstorff, A. (2008). Accessing the mental space—spatial working memory processes for language and vision overlap in precuneus. *Human Brain Mapping*, *29*(5), 524-532.

Waltz, J. A., Knowlton, B. J., Holyoak, K. J., Boone, K. B., Back-Madruga, C., McPherson, S., Masterman, D., Chow, T., Cummings, J. L., & Miller, B. L. (2004). Relational integration and executive function in Alzheimer's disease. *Neuropsychology*, *18*(2), 296-305.

Wang, K., Liang, M., Wang, L., Tian, L., Zhang, X., Li, K., & Jiang, T. (2007). Altered functional connectivity in early Alzheimer's disease: a resting-state fMRI study. *Human Brain Mapping*, *28*(10), 967-978.

Wang, L., Zang, Y., He, Y., Liang, M., Zhang, X., Tian, L., Wu, T., Jiang, T., & Li, K. (2006). Changes in hippocampal connectivity in the early stages of Alzheimer's disease: Evidence from resting state fMRI. *Neuroimage*, *31*(2), 496-504.

Wang, H. X., Gustafson, D. R., Kivipelto, M., Pedersen, N. L., Skoog, I., Windblad, B., & Fratiglioni, L. (2012). Education halves the risk of dementia due to apolipoprotein ε4 allele: A collaborative study from the Swedish Brain Power initiative. *Neurobiology of Aging*, *33*(5), 1007.e1-1007.e7.

Wang, R.F. (2012). Theories of spatial representations and reference frames: What can configuration errors tell us? *Psychonomic Bulletin & Review*, *19*(4), 575-587.

Washington, P. M., Villapol, S., & Burns, M. P. (2016). Polypathology and dementia after brain trauma: Does brain injury trigger distinct neurodegenerative diseases, or should they be classified together as traumatic encephalopathy? *Experimental Neurology*, *275*, 381-388.

Wassmann, J., & Dasen, P. R. (1998). Balinese spatial orientation: Some empirical evidence of moderate linguistic relativity. *Journal of the Royal Anthropological Institute*, 689-711.

Wechsler, D. (2010). *Wechsler Memory Scale–IV UK.* Harlow: Pearson.

Wechsler, D. (2010). *Wechsler Adult Intelligence Scale–IV UK.* Harlow: Pearson.

Wecker, N. S., Kramer, J. H., Hallam, B. J., & Delis, D. C. (2005). Mental flexibility: Age effects on switching. *Neuropsychology*, *19*(3), 345.

Weintraub, S., Wicklund, A. H., & Salmon, D. P. (2012). The neuropsychological profile of Alzheimer disease. *Cold Spring Harbor Perspectives in Medicine*, *2*(4): a006171.

Weiss, E. M., Ragland, J. D., Brensinger, C. M., Bilker, W. B., Deisenhammer, E. A., & Delazer, M. (2006). Sex differences in clustering and switching in verbal fluency tasks. *Journal of the International Neuropsychological Society*, *12*(4), 502-509.

Weiss, E. M., Siedentopf, C., Hofer, A., Deisenhammer, E. A., Hoptman, M. J., Kremser, C., & Delazer, M. (2003). Brain activation pattern during a verbal fluency test in healthy male and female volunteers: A functional magnetic resonance imaging study. *Neuroscience Letters*, *352*(3), 191-194.

Weniger, G., Ruhleder, M., Lange, C., Wolf, S., & Irle, E. (2011). Egocentric and allocentric memory as assessed by virtual reality in individuals with amnestic mild cognitive impairment. *Neuropsychologia*, *49*(3), 518-527.

West, R. L. (1996). An application of prefrontal cortex function theory to cognitive aging. *Psychological Bulletin, 120*, 272–292.

Whelan, R. (2008). Effective analysis of reaction time data. *The Psychological Record, 58*, 475-482.

Whitney, C., Kirk, M., O'Sullivan, J., Ralph, M. A. L., & Jefferies, E. (2012). Executive semantic processing is underpinned by a large-scale neural network: Revealing the contribution of left prefrontal, posterior temporal, and parietal cortex to controlled retrieval and selection using TMS. *Journal of Cognitive Neuroscience*, *24*(1), 133-147.

Wiegand, I., Töllner, T., Dyrholm, M., Müller, H. J., Bundesen, C., & Finke, K. (2014). Neural correlates of age-related decline and compensation in visual attention capacity. *Neurobiology of Aging*, *35*(9), 2161-2173.

Wiener, J. M., de Condappa, O., Harris, M. A., & Wolbers, T. (2013). Maladaptive bias for extrahippocampal navigation strategies in aging humans. *The Journal of Neuroscience*, *33*(14), 6012-6017.

Wiener, J. M., Kmecova, H., de Condappa, O. (2012). Route repetition and route retracing: Effects of cognitive aging. *Frontiers in Aging Neuroscience, 4*. doi:10.3389/fnagi.2012.00007.

Wierenga, C. E., Benjamin, M., Gopinath, K., Perlstein, W. M., Leonard, C. M., Rothi, L. J. G., Conway, T., Cato, M. A., Briggs, R., & Crosson, B. (2008). Age-related changes in word retrieval: Role of bilateral frontal and subcortical networks. *Neurobiology of Aging*, *29*(3), 436-451.

Williams, B. W., Mack, W., & Henderson, V. W. (1989). Boston Naming Test in Alzheimer's disease. *Neuropsychologia, 27*, 1073-1079.

Williamson, D. J., Adair, J. C., Raymer, A. M., & Heilman, K. M. (1998). Object and action naming in Alzheimer's disease. *Cortex*, *34*(4), 601-610.

Wilkniss, S. M., Jones, M. G., Korol, D. L., Gold, P. E., & Manning, C. A. (1997). Age-related differences in an ecologically based study of route learning. *Psychology and Aging*, *12*(2), 372-375.

Wingfield, A., & Grossman, M. (2006). Language and the aging brain: Patterns of neural compensation revealed by functional brain imaging. *Journal of Neurophysiology, 96*(6), 2830-2839.

Wingfield, A., McCoy, S. L., Peelle, J. E., Tun, P. A., & Cox, L. C. (2006). Effects of adult aging and hearing loss on comprehension of rapid speech varying syntactic complexity. *Journal of the American Academy of Audiology, 17*, 487-497.

Wingfield, A., & Stine-Morrow, E. A. L. (2000). Language and speech. In: Craik, F. I. M., & Salthouse, T. A. (Eds.). *The Handbook of Aging and Cognition* (pp. 155-220). Mahwah, NJ: Erlbaum.

Wolbers, T., & Hegarty, M. (2010). What determines our navigational abilities? *Trends in Cognitive Sciences*, *14*(3), 138-146.

Wolk, D. A., Dickerson, B. C., & Alzheimer's Disease Neuroimaging Initiative. (2011). Fractionating verbal episodic memory in Alzheimer's disease. *Neuroimage*, *54*(2), 1530-1539.

Wood, E. R., & Dudchenko, P. (2003). Aging, spatial behavior and the cognitive map. *Nature Neuroscience*, *6*(6), 546-548.

Woods, S. P., Scott, J. C., Sires, D. A., Grant, I., Heaton, R. K., Tröster, A. I., & HIV Neurobehavioral Research Center (HNRC) Group. (2005). Action (verb) fluency: Test-retest reliability, normative standards, and construct validity. *Journal of the International Neuropsychological Society*, *11*(4), 408-415.

Wu, D. H., Waller, S., & Chatterjee, A. (2007). The functional neuroanatomy of thematic role and locative relational knowledge. *Journal of Cognitive Neuroscience, 19*(9), 1542-1555.

Yamamoto, N., & DeGirolamo, G. J. (2012). Differential effects of aging on spatial learning through exploratory navigation and map reading. *Frontiers in Aging Neuroscience, 4*: 14.

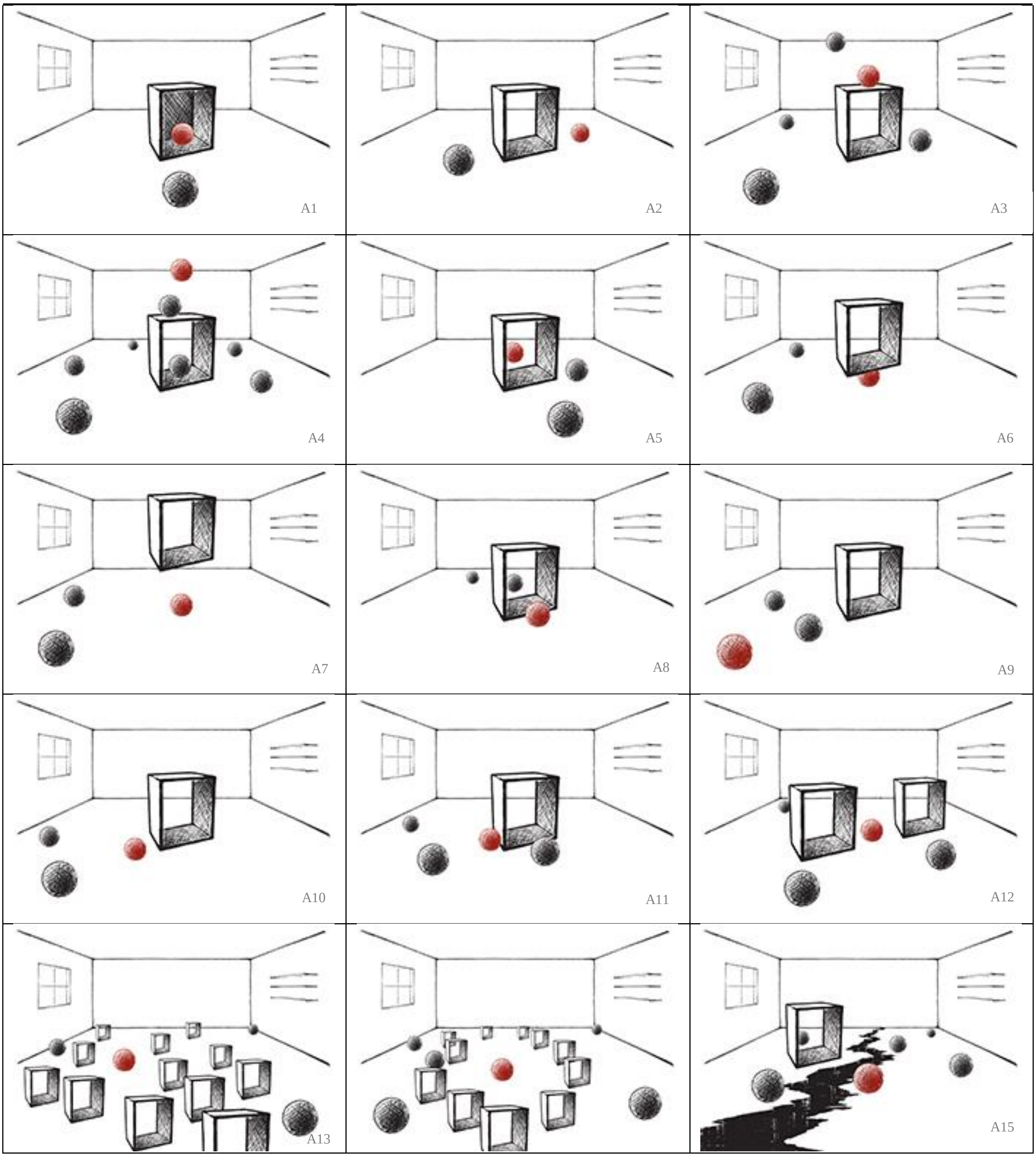
Yew, B., Alladi, S., Shailaja, M., Hodges, J. R., & Hornberger, M. (2013). Lost and forgotten? Orientation versus memory in Alzheimer's disease and frontotemporal dementia. *Journal of Alzheimer's Disease*, *33*(2), 473-481.

Ylikoski, R., Ylikoski, A., Erkinjuntti, T., Sulkava, R., Raininko, R., & Tilvis, R. (1993). White matter changes in healthy elderly persons correlate with attention and speed of mental processing. *Archives of Neurology*, *50*(8), 818-824.
Yonelinas, A.P. (2013). The hippocampus supports high-resolution binding in the service of perception, working memory and long-term memory. *Behavioural Brain Research, 254,* 34-44.
Yu, J. T., Tan, L., & Hardy, J. (2014). Apolipoprotein E in Alzheimer's disease: an update. *Annual Review of Neuroscience, 37*, 79-100.
Yuan, P., Daugherty, A. M., & Raz, N. (2014). Turning bias in virtual spatial navigation: age-related differences and neuroanatomical correlates. *Biological Psychology*, *96*, 8-19.
Zachariou, V., Klatzky, R., & Behrmann, M. (2014). Ventral and dorsal visual stream contributions to the perception of object shape and object location. *Journal of Cognitive Neuroscience*, *26*(1), 189-209.
Zacks, J. M. (2008). Neuroimaging studies of mental rotation: A meta-analysis and review. *Journal of Cognitive Neuroscience*, *20*(1), 1-19.
Zacks, J. M., & Michelon, P. (2005). Transformations of visuospatial images. *Behavioral and Cognitive Neuroscience Reviews*, *4*(2), 96-118.
Zacks, J. M., Mires, J., Tversky, B., & Hazeltine, E. (2002). Mental spatial transformations of objects and perspective. *Spatial Cognition and Computation, 2,* 315-332.
Zacks, J. M., Vettel, J. M., & Michelon, P. (2003). Imagined viewer and object rotations dissociated with event-related fMRI. *Journal of Cognitive Neuroscience*, *15*(7), 1002-1018.
Zalonis, I., Christidi, F., Bonakis, A., Kararizou, E., Triantafyllou, N.I., Paraskevas, G., Kapaki, E., & Vasilopoulos, D. (2009). The stroop effect in Greek healthy population: Normative data for the Stroop Neuropsychological Screening Test. *Archives of Clinical Neuropsychology*. doi:10.1093/arclin/acp011.
Zalonis, I., Kararizou, E., Triantafyllou, N. I., Kapaki, E., Papageorgiou, S., Sgouropoulos, P., & Vassilopoulos, D. (2008). A normative study of the Trail Making Test A and B in Greek adults. *The Clinical Neuropsychologist*, *22*, 842– 850.
Zancada-Menendez, C., Sampedro-Piquero, P., Lopez, L., & McNamara, T. P. (2016). Age and gender differences in spatial perspective taking. *Aging Clinical and Experimental Research*, *28*(2), 289-296.
Zelazo, P. D., Craik, F. I., & Booth, L. (2004). Executive function across the life span. *Acta Psychologica*, *115*(2), 167-183.
Zhou, X. H., McClish, D. K., & Obuchowski, N. A. (2009). *Statistical methods in diagnostic medicine*. New York: John Wiley & Sons.
Zhou, Y., Dougherty, J. H., Hubner, K. F., Bai, B., Cannon, R. L., & Hutson, R. K. (2008). Abnormal connectivity in the posterior cingulate and hippocampus in early Alzheimer's disease and mild cognitive impairment. *Alzheimer's & Dementia*, *4*(4), 265-270.
Zwarts, J. (1997). Vectors as relative positions: A compositional semantics of modified PPs. *Journal of Semantics*, *14*(1), 57-86.
Zwarts, J. (2005). Prepositional aspect and the algebra of paths. *Linguistics and Philosophy*, *28*(6), 739-779.
Zwaan, R. A. (2004). The immersed experiencer: Toward an embodied theory of language comprehension. *Psychology of Learning and Motivation*, *44*, 35-62.
Zwaan, R. A. (2014). Embodiment and language processing: Reframing the discussion. *Trends in Cognitive Sciences, 18(5),* 229-234.

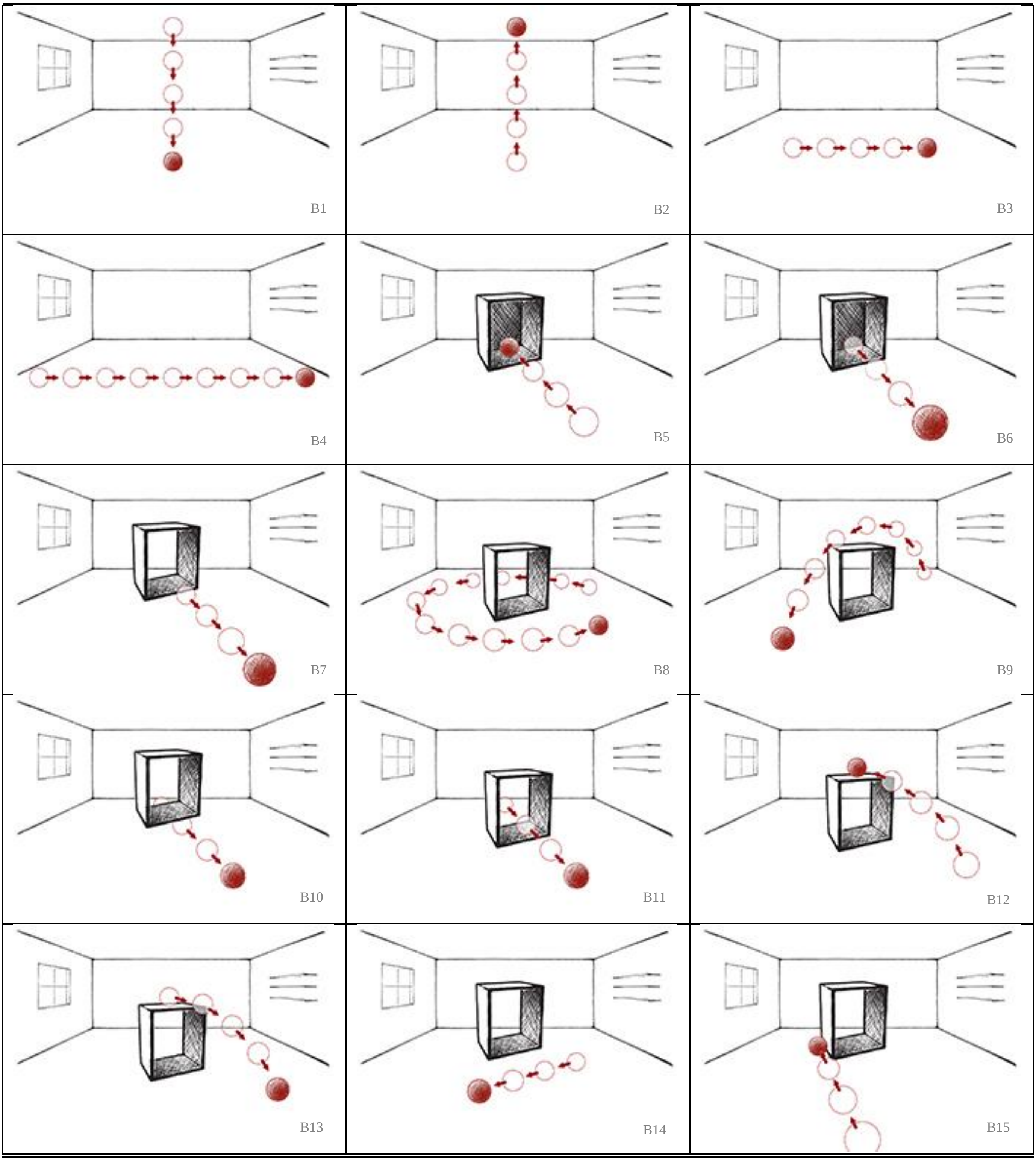
Appendix

Table A. *All stimuli of the Spatial Naming Test*

Part A



Part B



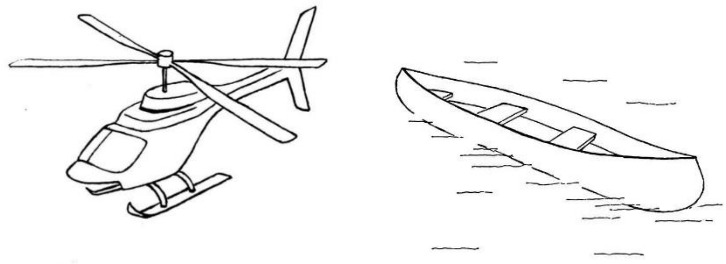


Figure A. Example test items (left: *helicopter*; right: canoe) of the Boston Naming Test (Kaplan, Goodglass, & Weintraub, 2001).

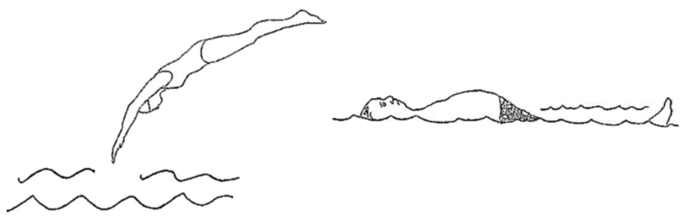


Figure B. Example test items (left: *diving*; right: *floating*) of the Action Naming Test (Obler & Albert, 1979).

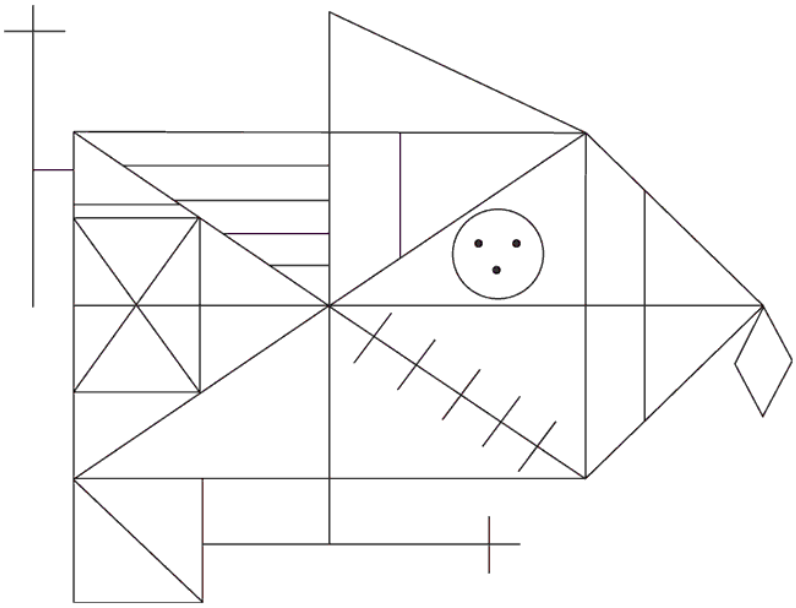


Figure C. The Rey-Osterrieth Complex Figure (Osterrieth, 1944; Strauss et al., 2006).

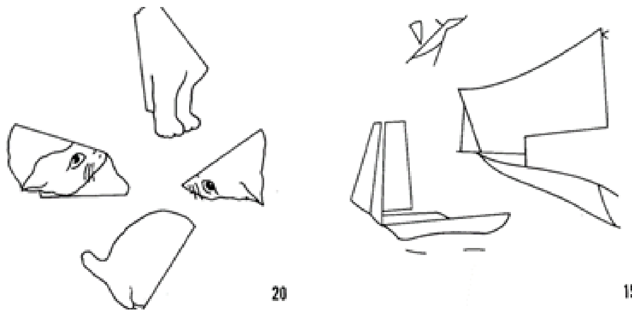


Figure D. Example test items (left: *cat*; right: *sailboat*) of the Hooper Visual Organization Test (Hooper, 1985).

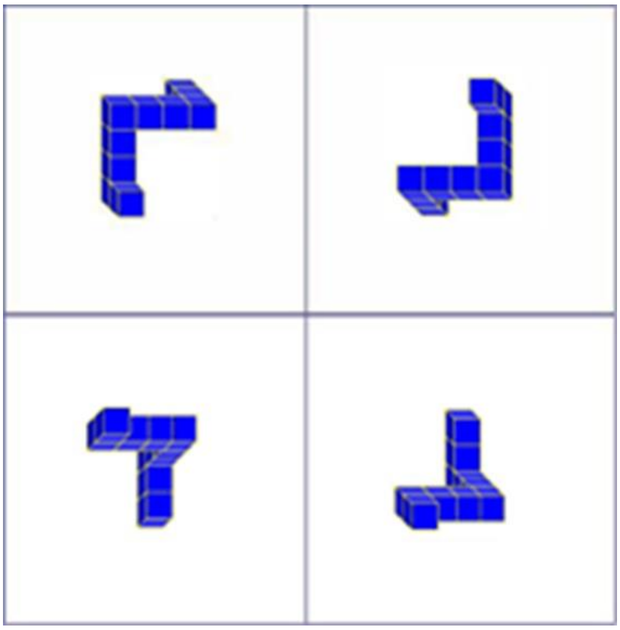


Figure E. Example test items (top pair: *same*; bottom pair: *different*) of the Mental Rotation Task (Shepard & Metzler, 1971).

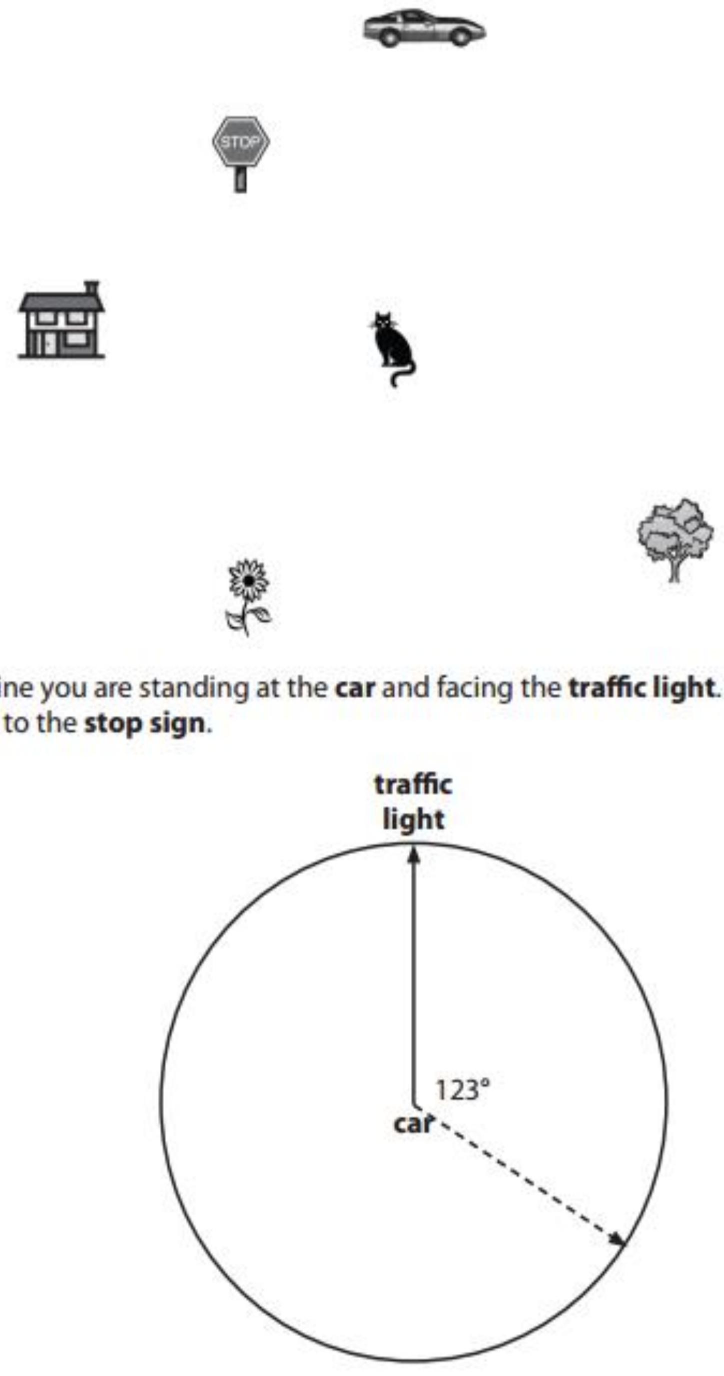


Figure F. Example item of the Object-Perspective Taking task (OPT; Hegarty & Waller, 2004; Kozhevnikov & Hegarty, 2001).

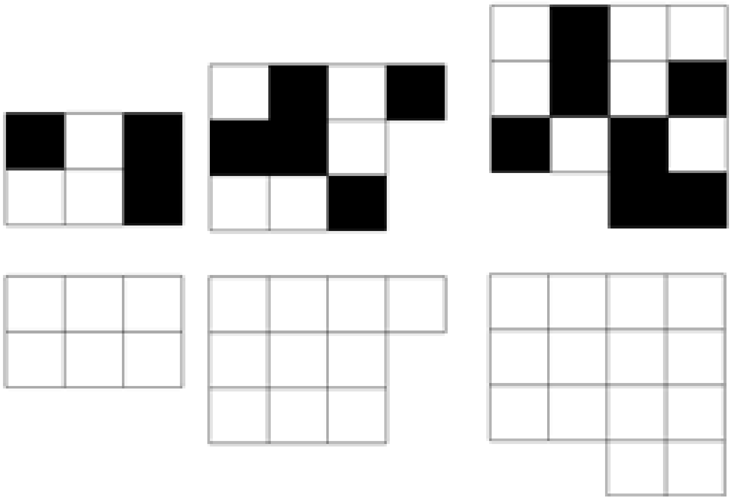


Figure G. Examples matrices of different levels of difficulty in the visual span test (Riby & Orme, 2013).