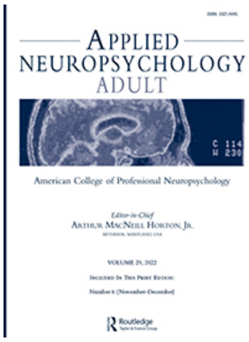

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Age effects on processing spatial relations within different reference frames: The role of executive functions

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ABSTRACT
Mental representations of space can be generated and communicated with respect to different reference frames and perspectives. The present study investigated the effects of age and individual differences in domain-general executive functions on people's ability to process spatial relations as expressed in language within different spatial reference frames (SRFs). Healthy adults aged between 18 and 85 completed a novel task involving self-, third-person-, object-, and environment-centered judgements of spatial relations between two objects, as well as standard tests of working memory, inhibition, and mental flexibility. A psychometric evaluation confirmed the test-retest reliability and the convergent and divergent validity of the new task. Results showed that the lifespan trajectories varied depending on the SRF. Processing from a self-centered perspective or an object-centered frame remained intact throughout the adult-lifespan. By contrast, spatial processing from a third-person-centered perspective or within an environment-centered frame declined in late adulthood. Mediation regression models showed that mental flexibility accounted for a significant part of the age-related variance in spatial processing across all allocentric SRFs. The age effects on environment-centered processing were also partially mediated by age-related changes in visuospatial working memory capacity. These findings suggest that at least partially distinct systems are involved in mentally representing space under different SRFs, which are differentially affected by typical aging. Our results also highlight that people's ability to process spatial relations across different SRFs depends on their capacity to employ domain-general effortful cognitive resources.

KEYWORDS
Aging; executive functions; spatial cognition; spatial perspective-taking; spatial reference frames

Introduction

The ability to mentally represent and communicate spatial relations with respect to different perspectives and spatial frames of reference is an important aspect of cognition across various contexts, which extend from everyday social interaction and wayfinding to technical domains such as architecture and air traffic control. Yet, it is not clear whether the processing demands are comparable across different spatial frames of reference, how this ability may change with increasing age, and what underlying cognitive mechanisms support it. The present study focuses on these issues.

Spatial reference frames

Communicating spatial relations with verbal means lies at the crossroads of perception and language (Markostamou & Coventry, 2022), as the perceptual input of spatial relations in the environment and the words describing them are mapped onto mental representation of space (Carlson, 1999). These mental representations may employ different spatial reference frames (SRFs), i.e., coordinate axial systems relative to which spatial relations are defined, based on different sources of information (Carlson, 1999; Levinson, 2003). SRFs can be based on one's own point of view (relative SRF), a facet of a reference object (intrinsic SRF), or an external point in the environment (absolute SRF) (Levinson, 2003). Within an environment-centered SRF, spatial relations are defined by salient environmental points, such as cardinal directions (e.g., *The library is located north of the Cathedral*). In an object-centered SRF, spatial relations are defined by the intrinsic orientation/direction of the reference object and can be binary (e.g., *The coffee table is in front of the sofa*) or ternary with the presence of an agent defining the coordinate system (e.g., in a person-centered SRF, *The coffee table is to the left of the sofa*). The binary or ternary spatial relations within these SRFs are independent from a particular self-centered viewpoint, which may or may not be aligned with these SRFs. By contrast, the self-centered SRF establishes binary or ternary viewpoint-dependent spatial relations.

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In broad terms, spatial perspective-taking can be defined as the ability to imagine how objects or spatial relations look from a perspective other than our own (Kessler & Rutherford, 2010; Zacks et al., 2000). Being able to represent and communicate where people and objects are located in the environment within different frames of reference is essential for numerous daily activities and in various social contexts. For example, consider how one may encode and process object locations and spatial relations within various SRFs in an ordinary situation like driving on the road to reach a colleague's house-warming party. At first, the driver needs to realize that their colleague's house is located north of the city's river (environment-centered SRF). Then, they need to find the bridge that lies in front of the train station (object-centered SRF), and from there to head toward the north. Meanwhile, they need to constantly process the locations and the spatial relations of various objects (such as other moving cars or cars which are parked at the side of road, road marks, etc.) with respect to their own changing viewpoint and orientation (self-centered SRF), as well as from the changing perspective of other fellow drivers or pedestrians (third-person-centered SRF). Being able to represent spatial relations from all these different SRFs will allow our protagonist to effectively plan a precise route and follow it, as well as to mentally simulate and predict how spatial relations may change in the dynamic environment of a road and adjust their driving accordingly.

Spatial mental representations have also been classified as egocentric, reflecting the spatial relations' dependence on the particular perceptual perspective of one's self, while SRFs in which spatial relations are invariant to a self-centered viewpoint have been classified as allocentric (Colombo et al., 2017). It has been proposed that multiple SRFs are spontaneously activated while making judgements of spatial descriptions, by constructing a composite spatial template which includes representations from all possible coordinate systems (Carlson, 1999). However, some researchers consider allocentric spatial processing to be inherently more demanding than egocentric processing (Surtees & Apperly, 2012). This view ascribes precedence to an egocentric processing of representing space (Shelton & McNamara, 2001), and is based on the assumption that the egocentric frame can be accessed directly through our perceptual systems without any coordination processes, whereas the externally-grounded nature of allocentric processing requires additional integration processing of spatial relations, involving mental alignments between an imagined perspective and the orientations of the reference and located objects (Kozhevnikov & Hegarty, 2001; Shelton & McNamara, 2001).

Spatial reference frames and aging

Impairments in spatially perceiving the world based on different SRFs and perspectives can have a significant impact on people's daily activities and can undermine independent living. Thus, it is important to examine how processing spatial locations from different SRFs may change as one ages. Past research has mainly examined the effects of aging on egocentric and allocentric spatial processing during memory and navigation tasks employing either real-world settings or virtual environments (Colombo et al., 2017; Klencklen et al., 2012; Muffato et al., 2019; 2020). According to studies focusing on memory, there seems to exist a generalized deficit in the acquisition of allocentric knowledge amongst older adults (Gazova et al., 2013), with a greater vulnerability when encoding spatial information from an environment-centered SRF compared to object- and self-centered frames (Montefinese et al., 2015). Nevertheless, age-related impairments in the retrieval of both visually- (e.g., Muffato et al., 2019, 2020; Ruggiero et al., 2016) and verbally-encoded (e.g., Markostamou & Coventry, 2021) egocentric spatial information have also been reported. In navigation, older adults clearly prefer using egocentric strategies and exhibit difficulties in effective and appropriate use of allocentric place strategies (Harris et al., 2012; Rodgers et al., 2012). However, age-related difficulties in navigation may also be associated with switching costs in tasks that require alternating between egocentric and allocentric strategies (Harris et al., 2012; Wiener et al., 2013), suggesting that domain-general executive functions might play a significant role in spatial processing within different SRFs.

Other than memory and navigation studies, in which spatial relations must be retrieved from memory, research on visuospatial perspective-taking in perceptually available spatial scenes has proceeded along two rather separate lines for spatial and social contexts. In the absence of another social agent, studies have employed pointing or reconstruction tasks in order to examine age effects on visuospatial perspective-taking (Borella et al., 2014; Inagaki et al., 2002; Zancada-Menendez et al., 2016). For example, using a variant of Piaget's three-mountain task (3MT), which requires participants to imagine how an array of real objects would look from a different viewpoint and reconstruct it using blocks, two studies (Inagaki et al., 2002; McDonald & Stuart-Hamilton, 2002) reported impaired perspective-taking abilities in older adults compared to middle-aged and younger adults, with the number of egocentric errors increasing with age. Similarly, using a pointing task (Kozhevnikov & Hegarty, 2001), in which participants are shown a two-dimensional array of objects on a piece of paper, imagine taking a perspective within the array, and point toward a third object from the imagined perspective, two studies also found an age-related decline in spatial perspective-taking, which was apparent from middle-aged adults (Borella et al., 2014; Zancada-Menendez et al., 2016).

Another line of research has focused on perspective-taking in social contexts, often in dialogue. Because interlocutors may have separate perspectives, they are often required to engage in perspective-taking to establish a common SRF with their conversation partner when referring to objects or spatial relations in order to overcome potential referential ambiguities. Simple visual perspective-taking, the ability to represent whether another person can or cannot see a certain object (also known as Level-1 perspective-taking; Flavell et al., 1981; Michelon & Zacks, 2006), is believed to

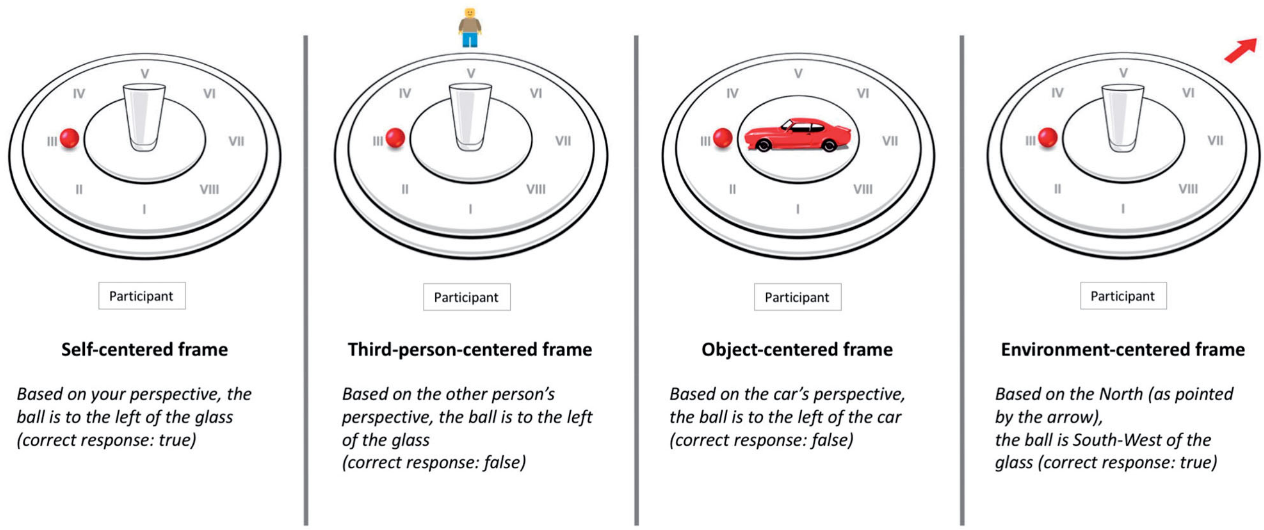

Figure 1. Schematic representation of the apparatus and all spatial reference frames in the Spatial Referencing Task. *Note.* The middle circular board is rotated to move the located object (red ball) into the eight test locations (Latin numbers) relatively to the reference objects (glass, car). Test locations are not marked on the apparatus to eliminate the possibility of being used as facilitating cues by the participants.

occur automatically (i.e., without people being prompted; Heller et al., 2008; Surtees & Apperly, 2012). Visuospatial perspective-taking, the ability to represent how another person sees something (also known as Level-2 perspective-taking; Flavell et al., 1981; Michelon & Zacks, 2006), is thought to be an effortful process (Kessler & Thomson, 2010; Michelon & Zacks, 2006), which requires some cognitive control in order to overcome egocentric interference (Surtees et al., 2016). Nevertheless, people can flexibly switch from a self- to a third-person-centered visual perspective despite the greater processing costs associated with taking another person's perspective (Duran et al., 2011; Galati et al., 2018). This flexible mental switch in perspectives enables the two interlocutors' mental representations of space to be aligned, and ultimately ensures optimum communication.

To date, very few studies have investigated the effects of aging on the ability to take another person's visual or spatial perspective. A study employing interactive discourse tasks found that older adults had reduced capacity to adopt another person's visual perspective (Long et al., 2018). An age-related egocentric processing bias has also been observed in perceptual matching tasks of visual perspective-taking (Mattan et al., 2017). However, these results are limited to Level-1 visual perspective-taking, thus questions remain regarding the effects of aging on processing spatial relations from a third-person-centered perspective.

The present study

In the present study, younger, middle-aged and older adults completed a novel task which involved judging verbal descriptions of spatial relations between two three-dimensional objects in a perceptually available scene of the physical environment (e.g., *The red ball is to the left of the glass*) within four distinct SRFs: self-, third-person-, object-, and environment-centered frames (see Figure 1). The inclusion of these SRFs was based on Levinson's (2003) classification system and previous language (e.g., Coventry et al., 2018), memory (e.g., Montefinese et al., 2015), and neuroimaging (e.g., Committeri et al., 2004; Galati et al., 2010; Marchette et al., 2014; Sulpizio et al., 2013) studies focusing on spatial reference frames, as well as studies examining visuospatial perspective-taking in social contexts (e.g., Duran et al., 2011; Galati et al., 2018; Surtees et al., 2016). The paradigm we employ should enable us to objectively obtain performance measures of accuracy and speed for each SRF separately and then directly compare them from an adult-lifespan perspective.

Based on evidence indicating that people are able to mentally represent and assign appropriate spatial terms for spatial relations under different SRFs (Carlson, 1999; Coventry et al., 2018), we hypothesized that participants' performance across all frames would be well above chance level in our paradigm. However, in line with the neuroimaging findings indicating partially dissociable neural correlates for spatial processing relative to different SRFs (Committeri et al., 2004; Galati et al., 2010; Sulpizio et al., 2013), we expected SRF-dependent differences on chronometric and accuracy performance, with lower accuracy and/or slower speed in allocentric frames, especially in the environment-centered frame. We also expected different lifespan trajectories of task performance as a function of the SRF. Specifically, minimal or no age effects should be observed in egocentric spatial processing, while processing spatial relations relative to another person, an object, or an external environmental point should be sensitive to aging effects. Moreover, any age-related changes in the third-person- and environment-centered SRFs are expected to be more accentuated compared to object-centered spatial processing, in line with previous findings from memory paradigms (Montefinese et al., 2015). Finally, given the pivotal role of the hippocampus in supporting environment-centered spatial processing abilities (Mitchell et al., 2018; Sulpizio et al., 2013) and that hippocampal regions undergo significant structural and functional changes with increasing age (Konishi & Bohbot, 2013; Ramanoël et al., 2019), we expected to observe striking age effects in environment-centered spatial processing.

Another objective of the present study was to examine to what extent spatial perspective-taking performance is correlated with executive functioning measures, and, if so, whether executive functions explain potential age-related differences in processing spatial descriptions within different SRFs. Individual differences studies with young adults have shown that Level-1 perspective-taking is positively correlated with both working memory and inhibition control measures (Wardlow, 2013) and that inhibitory control may predict Level-1 perspective-taking performance during discourse paradigms (Brown-Schmidt, 2009). In line with these studies, dual-task paradigms involving young adults have revealed that the ability to adopt a third person's visual perspective is disrupted when performed concurrently with a response inhibition tapping task (Qureshi et al., 2010). There is currently only one published study focusing on the other end of the lifespan (Long et al., 2018), which found older adults' Level-1 perspective-taking ability during language comprehension to be associated with domain-general attentional switching performance.

Taken together, the evidence presented above points to links between perspective-taking and executive functioning. However, existing findings have been limited to Level-1 perspective-taking, while prior work has not examined the simultaneous contributions of different aspects of executive functioning in locative spatial processing across different SRFs in aging. In the current study, we followed up the notion that executive functions play a prominent role in spatial processing within different SRFs. We assessed individual differences in the most commonly postulated executive functions, which include inhibitory control, mental flexibility (also called set shifting or attentional switching), and updating and monitoring working memory representations (Miyake et al., 2000). These mental processes are considered to be general-purpose control mechanisms that regulate everyday behavior and enable successful performance on novel or complex cognitive tasks (Diamond, 2013). We hypothesized that greater domain-general executive resources would enable participants to more efficiently inhibit a putative egocentric spatial processing bias, flexibly switch and adapt to a different SRF, and efficiently maintain and manipulate spatial representations in their working memory system, leading to better performance in our task. Moreover, as executive functions are particularly sensitive to age-related decline (Albinet et al., 2012), it was expected that they should, at least partially, explain potential aging effects on processing spatial relations within different SRFs.

In summary, in the present study we employed a new task, in which participants were asked to make verification judgements of spatial descriptions across self-, third-person-, object-, and environment-centered SRFs, in order to address the following research questions: (1) Is the capacity for processing spatial relations comparable across these different frames of reference or does processing speed and accuracy change depending on the SRF involved? (2) What are the adult-lifespan trajectories of these spatial processes? Are these processes differentially vulnerable to increasing age? (3) Are these processes associated with the domain-general executive functions of inhibitory control, mental flexibility, and working memory? To what extent can executive functioning resources explain putative age-related changes in spatial processing within different SRFs? Before addressing these questions, we first examined the psychometric properties of our novel task and established its test-retest reliability and construct validity. For the reliability assessment, strong correlations and absence of differences between SRT performance across two separate time points would provide evidence of the task's temporal stability. In testing its convergent validity, we expected task performance to correlate with performance in a conventional pointing task of spatial perspective-taking. Lower correlations between dissimilar measures, i.e., performance in our novel task and performance in an unrelated task verbal fluency task, were hypothesized to indicate divergent validity.

Method

Participants

One hundred and sixty-four individuals took part in the present study. Participants were selected in order to cover a broad age range spanning from 18 to 85 years and to form five main groups of younger, middle-aged, and older adults, stratified by 10-year age brackets (18–28, 45–54, 55–64, 65–74, 75–85 years; $N = 30–34$ per age group). The selection of participants aged between 45 and 85 was based on further classification of individuals by age in half-decades (i.e., 45–49, 50–54, 55–59 years, and so on; $N = 15–16$ per age subgroup) to achieve optimum age distributions for the main age groups in our sample. The size of the sample was based on an *a priori* power analysis using G*Power (Faul et al., 2007), where we converted a conservative effect size ($\eta_p^2 = .09$) to Cohen's $f = .31$ and used a power of .8 and $\alpha = .05$ for the estimation with five groups and four measurements, which indicated that 160 participants were needed. Younger individuals in their 30 s were not recruited because of practical difficulties in recruiting individuals of this age due to their demanding daily schedules.

Exclusion criteria for all participants included prior history of head injury, substance dependence, severe learning or intellectual disability, and any active medical, neurological, or psychiatric disorders resulting in cognitive dysfunction. All participants spoke English as their first language and had normal or corrected-to-normal vision and hearing. Inclusion criteria included absence of a subjective memory complaint (i.e., had not sought professional assessment due to concerns about their memory) and a score $\geq$ 25 on the MoCA (Nasreddine et al., 2005), a brief measure of general cognitive functioning. The final adult-lifespan sample consisted of 160 participants, as four participants were excluded for not meeting all criteria.

Table 1 presents participants' characteristics within each age group. Participants' selection followed a balanced gender representation in each age group, $\chi^2(4) = 2.63$, $p > .250$. There were no illiterate participants in our sample, however, the 45–54 and 55–64 groups had a higher level of education than the 75–85 group, and the 45–54 group had more years of formal schooling than the 65–74 group (Table 1). Our participants also completed the Mill Hill Vocabulary Test (MHVT; Raven & Court, 1998) and self-report measures for depression (PHQ-9; Kroenke et al., 2001) and anxiety (GAD-7; Spitzer et al., 2006) to ensure that any superiority in spatial processing among younger adults was not likely to be due to higher crystallized intelligence or better emotional well-being. Younger adults aged 18–28 had lower vocabulary scores than all other age groups (Table 1). Moreover, participants in the 18–28 group reported reliably higher levels of depression and anxiety than all other age groups (Table 1).

Materials and measures

Spatial Referencing Task (SRT)

The SRT was developed to assess the ability to process descriptions of spatial relations between two objects in a perceptually available scene in the physical environment within different spatial reference frames (SRFs). The task was designed to include four distinct SRFs: (1) a self-centered, (2) a third-person-centered SRF, (3) an object-centered SRF, and (4) an environment-centered SRF. While in the self-centered frame spatial relations are encoded egocentrically, relatively to the examinee's viewpoint, successful processing of spatial relations in the other SRFs requires spatial perspective transformations. More specifically, in the third-person-centered SRF, spatial relations were defined relative to another person's viewpoint, requiring the examinee to adopt the third-person's perspective. The object-centered SRF involved binary spatial relations defined by the axial orientation of the reference object. Finally, under the environment-centered frame, spatial relations were described with respect to a fixed point in the external environment. Figure 1 provides a schematic representation of all four SRFs of the task, along with the general instructions used in each frame and an example description of a spatial relation between the located and the reference objects.

Apparatus and stimuli. The SRT apparatus consisted of a central circular board with a diameter of 18 cm, on which the reference object was placed, surrounded by a rotating circular board with a diameter of 28 cm, on which the located object was placed, based on a third stable circular board with a diameter of 37 cm. The middle board of the apparatus was rotated in order to move the located object into eight different locations relative 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 (Figure 1).

Table 1. Participants' characteristics across all age groups.

	Age group (years)								
	18–28	45–54	55–64	65–74	75–85	Total	*F*(4,155) value	Effect size (η_p^2)	Post-hoc group comparisons
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 (20.60)			
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)	7.35**	.16	45–54 > 75–85* 45–54 > 65–74* 55–64 > 75–85*
Gender (% females)	52%	68%	59%	53%	62%	59%			
General cognitive functioning (MoCA)	–	29.31 (1.05)	27.93 (1.92)	27.75 (1.54)	26.43 (1.50)	27.68 (1.82)			
Vocabulary (MHVT)	18.00 (3.45)	22.60 (4.42)	22.75 (3.75)	23.47 (3.54)	23.37 (4.03)	21.98 (4.33)	11.89**	.23	18–28 < 45–54** 18–28 < 55–64** 18–28 < 65–74** 18–28 < 75–85**
Depression (PHQ-9)	6.00 (4.43)	3.33 (4.04)	3.16 (3.93)	2.19 (2.45)	1.59 (1.64)	3.29 (3.76)	7.9**	.17	18–28 > 45–54* 18–28 > 55–64* 18–28 > 65–74* 18–28 > 75–85*
Anxiety (GAD-7)	6.68 (4.63)	3.50 (3.97)	3.62 (3.51)	2.34 (2.79)	2.00 (2.51)	3.67 (3.92)	8.86**	.19	18–28 > 45–54* 18–28 > 55–64* 18–28 > 65–74* 18–28 > 75–85*

Note. Values represent means (and standard deviations); $^*p < .05$; $^{**}p < .001$.

Common three-dimensional objects were used as the reference and located objects across all SRFs. To avoid ambiguity, we used an object (a glass) with no extrinsic parts and features as the reference object in the self-, third-person-, and environment-centered SRFs. By contrast, a concrete object (a miniature model car) with definite extrinsic parts was used as the reference object in the object-centered SRF and was placed at an angle of 90 degrees to the left of the participant (Figure 1). In the third-person-centered SRF, a Lego mini-figure, facing the reference object, was placed directly opposite of the participants' location (at an angle of 180 degrees; Figure 1). In the environment-centered SRF, an arrow pointing to the North was placed approximately 150 cm away from the participant at a right angle of 45 degrees (Figure 1). The arrow (measuring approximately 15×21 cm) was positioned in such way that it was pointing toward the actual geographic north in order to enhance the ecological validity of the task. A concrete object with no extrinsic parts (a ball with a diameter of 3 cm) was used as the located object across all SRFs. This choice of reference locations ensured that each frame was clearly separable from each other and that each frame-defining object was not aligned or opposite the others.

Procedure. Participants sat in front of the apparatus, on which the located and reference objects were placed. It was explained that they would be hearing a number of verbal statements describing spatial relations between the two objects placed on the apparatus, and that they would be required to judge each statement as true or false (e.g., *The ball is to the left of the glass*). Each reference frame was explained at the outset of each block, and participants were explicitly given instructions as to which reference frame they should base their judgements on for each condition (e.g., in the object-centered frame: *This time, you should base your judgments with reference to the car's perspective*). All participants understood the instructions without difficulty. An example trial was also provided at the start of each SRF (with further instructions provided if the participant's response was not correct) to ensure task instructions were fully understood.

For all participants, the baseline self-centered SRF was administered first in order to introduce participants to the task, and then the remaining SRF blocks were administered consecutively in a random order. There was a total of 64 test trials across all SRFs (16 test trials in each one of the four SRFs), with 50% of the spatial descriptions being true. Each spatial relation was described with one out of eight possible spatial labels (*in front of*, *behind of*, *to the left of*, *to the right of*, *in front and to the left of*, *in front and to the right of*, *behind and to the left of*, and *behind and to the right of*; or *north of*, *south of*, *east of*, *west of*, *north-east of*, *north-west of*, *south-east of*, and *south-west of* in the environment-centered frame). Test trials in each SRF block were presented in a randomized order.

Scoring. The percentage of correct responses was calculated as an index of processing accuracy in each SRF, hence, higher scores indicated better performance. There was no time limit in completing the task, but the time required for each participant to judge each spatial description was recorded with a handheld stopwatch. Mean response latencies (in ms) for each SRF were calculated as an index of processing speed, hence, lower scores indicated faster speed. Composite accuracy and speed scores were also calculated.

Executive function measures

We used three well-established neuropsychological tasks to assess three core executive functioning abilities, including inhibitory control, mental flexibility, and working memory capacity (Diamond, 2013; Miyake et al., 2000). The Stroop task (ST; Golden, 1978) was used as a measure of inhibitory (or interference) control, as it requires suppressing a prepotent response in favor of an unusual one to successfully complete the task. Participants were shown a list of color words printed in colors they did not represent, and were asked to name the color of the ink instead of reading the written words. Performance was based on the number of correct responses given in 45 s, hence, higher scores indicated better performances.

Part B of the Trail Making Test (TMT; Reitan, 1958) was used as a measure of mental flexibility (or set shifting). Participants had to connect a series of numbers and letters in an ascending numerical and alphabetical order while alternating between numbers and letters, 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 to ensure their understanding. The time required to complete the task was recorded as the dependent variable, with higher scores indicating worse performance.

The backward condition of the Corsi blocks task (CB-B; Corsi, 1972) was used as a measure of visuospatial working memory capacity. In this task, the experimenter pointed to a series of blocks randomly placed on a board, and the participant had to repeat the sequence of blocks in the reverse order. 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 after two consecutive recall errors. The final score was based on the maximum length of the correctly recalled sequences.

Tests used for the validity assessment

We used the Spatial Orientation Test (SOT; Kozhevnikov & Hegarty, 2001) and a phonemic verbal fluency task (Aita et al., 2019) in order to examine to convergent and divergent validity of the SRT, respectively. The SOT is a paper-and-pencil spatial test assessing object-based perspective taking. It consists of 12 pictures, each containing a set of objects and an "arrow circle." In each item, participants had to imagine they were standing at one object in the array, facing another object, and then draw an arrow from the center of the circle pointing to a third object from that facing orientation. Participants had a total of five minutes to complete the task. The angular error of each response was calculated with a protractor, and the average degrees of error were calculated as the dependent variable.

Phonemic verbal fluency is a widely used executive language task (Aita et al., 2019). Across three trials, participants were asked to generate as many words beginning with a particular letter (*F*, *A*, or *S*) as possible, in one minute, avoiding first names, repetitions and variations of the same word. Performance was based on the total number of correct responses generated across all trials.

General procedure

The study was formally approved by the University of East Anglia's School of Psychology Ethics Committee and all procedures were carried out in full compliance with the BPS guidelines and the 2013 Declaration of Helsinki. Participants were recruited from East Anglia regions of the UK through advertisements in local media, invitation leaflets, and word of mouth. All participants took part voluntarily and provided written informed consent prior to participation. Participants received a monetary compensation for their participation, with the exception of about two thirds of the participants in the 18–28 age group, who received course credits for taking part.

All participants were tested in a single lab session lasting approximately two hours on an individual (one-to-one) basis. At the outset of each session, participants provided health and demographic information, followed by the MoCA administration in adults aged 45 or more. Apart from the measures considered here, participants also completed other cognitive tasks (such as memory tests), that are beyond the scope of the present paper. All tasks were presented in a printed format and were administered in a randomized order (except for memory tests that involved delayed recall trials after specific time intervals).

Results

Data screening

Statistical analyses were conducted using SPSS 27.0 (IBM Corp., Armonk, NY). There were no missing points in the data sets. Data points that were more than 3.0 standard deviations from the mean of each variable were considered outliers, and there were two data points meeting this criterion (i.e., less than 1% of the total). Because there were so few univariate outliers, we chose to replace each with the mean score of that variable (Gravetter et al., 2020). We examined Cook's *D* to assess multivariate outliers, however, there were no variables greater than 1.0 (Gravetter et al., 2020).

Psychometric properties of the SRT

Distribution of performance

We inspected the distribution of performance of the adult-lifespan sample on all experimental conditions of the SRT to determine the presence of any floor or ceiling effects. Descriptive statistics for the accuracy scores in the SRT are presented in Table 2. The skewness and kurtosis values indicated that the distribution of scores departed from normality in the self-, third-person-, and object-centered frames, where participants performed close to or at ceiling levels. 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 on accuracy scores were present in any of the SRFs, reflecting a low task-difficulty for typically aging adults.

Test-Retest reliability assessment and practice effects

A subgroup of 32 healthy adults (18 females), ranging in age from 21 to 54 years (age: $M = 36.3$, $SD = 10.21$ years; years of formal education: range = 13–21, $M = 15.03$, $SD = 2.92$ years), completed the task on a second occasion, with a testing interval of between 2 and 24 weeks. Pearson product-moment correlations between the two testing sessions were calculated across accuracy and speed scores to examine the test-retest reliability of the task. Test-retest means (percentage of correct responses and average response latencies) and reliability coefficients are presented in Table 3. Reliability coefficients for accuracy scores ranged between .85 and .88 and for speed scores between .76 and

Table 2. Descriptive statistics for accuracy and speed scores in the Spatial Referencing Task.

					Distribution	
	Mean	SD	Min	Max	Skewness	Kurtosis
Accuracy scores (% correct)						
Composite accuracy score	93.81	6.49	67.19	100.00	−1.3	1.52
Self-centered	99.96	.49	93.75	100.00	−12.65	160.00
Third-person-centered	97.22	7.71	50.00	100.00	−3.91	19.94
Object-centered	96.09	9.58	37.50	100.00	−3.79	16.95
Environment-centered	81.99	19.93	12.50	100.00	−1.32	1.52
Speed scores (average response latencies in ms)						
Composite speed score	1,950	635	422	3,672	.43	−.06
Self-centered	1,384	478	375	2,875	.66	.50
Third-person-centered	1,714	697	375	3,687	.68	−.22
Object-centered	1,408	613	313	3,312	.84	.14
Environment-centered	3,293	997	625	5,812	.25	.10

Note. $N = 160$.

Table 3. Test-retest data for accuracy (proportion of correct responses) and speed (average response latencies in ms) and correlation coefficients for the Spatial Referencing Task.

	Session 1		Session 2		
	M	*SD*	*M*	*SD*	*r*
SRT: Composite accuracy	96.56	4.19	96.72	4.69	.86*
SRT: Composite speed	1,570	530	1,210	520	.87*
Self-centered: Accuracy	100.00	0.00	100.00	0.00	—
Self-centered: Speed	1,180	420	820	420	.90*
Third-person-centered: Accuracy	99.07	2.29	99.06	2.29	.85*
Third-person-centered: Speed	1,520	780	1,190	640	.81*
Object-centered: Accuracy	99.38	1.92	100.00	0.00	—
Object-centered: Speed	1,030	340	810	260	.77*
Environment-centered: Accuracy	87.81	16.53	87.82	17.49	.88*
Environment-centered: Speed	2,530	960	2,040	780	.76*

Note. $N = 32$; * $p < .001$.

.90. Paired-samples t tests were performed to compare mean scores between the two sessions for each SRF. Results showed that speed scores were subject to a practice effect. Participants performed faster across all SRFs on the second administration of the SRT [self-centered: $t(31) = 8.35$, $p < .001$; third-person-centered: $t(31) = 3.24$, $p = .004$; object-centered: $t(31) = 4.88$, $p < .001$; environment-centered: $t(31) = 3.60$, $p = .002$]. No practice effects were detected on accuracy scores ($p > .250$), providing further evidence for the test-retest reliability of the SRT.

Validity assessment

A subgroup of 114 participants (65 female), aged between 23 and 84 years of age ($M = 63.42$, $SD = 12.12$) with an average of 14.01 ($SD = 3.44$) years of formal education, completed the SOT and the verbal fluency task. Pearson's correlations were used to examine the concurrent validity of the SRT with respect to the SOT, a similar task that assesses spatial perspective-taking, and its divergent validity with respect to a dissimilar verbal fluency task. Results (Table 4) showed significant correlations between SRT and SOT performance ($r_s = -.28$ to $-.59$, $p_s \leq .01$), while no correlations were revealed between SRT and verbal fluency ($r_s = .02$ to $.12$, $p \geq .109$). We also conducted partial correlations between measures, controlling for age effects, to ensure that the observed associations were not inflated by age-related coupled changes. The age-controlled analysis yielded similar results (Table 4). These results provide good evidence of convergent validity for the SRT with respect to another measure of spatial perspective-taking and of divergent validity with respect to a dissimilar executive language measure.

Performance on the SRT

Mixed factorial analysis of variance was employed to examine the effects of age group (between-subjects variable with five levels) and spatial reference frame (SRF; within-subjects variable with four levels), and their possible interaction effects on task performance. For both accuracy and speed scores, partial eta-squared (η_p^2) is indicated as a measure of effect size. Significant main effects were followed-up with Bonferroni-corrected *post hoc* group comparisons. Significant main interaction effects were followed-up with tests of simple effects with Bonferroni correction, in order to allow comparisons between age groups for any given spatial reference frame. Figure 2 illustrates performance based on accuracy (percentages of correct responses) and speed (average response latencies) across each SRF. Figure 3 shows performance based on accuracy (percentages of correct responses) and speed (average response latencies) across all SRFs for each age group.

Table 4. Bivariate (and partial) correlations between Spatial Referencing Task performance, Spatial Orientation Test performance, and verbal fluency.

Measure	1	2	3	4	5	6	7
1. SRT composite score	–	.02 (.05)	.57** (.53**)	.54** (.56**)	.89** (.89**)	−.59** (−.55**)	.08 (.01)
2. SRT self-centered		–	.05 (.02)	.04 (.04)	.06 (.08)	−.13 (−.09)	.02 (.01)
3. SRT third-person-centered			–	.30** (.31**)	.29** (.23*)	−.29** (−.25*)	.03 (.12)
4. SRT object-centered				–	.26* (.21*)	−.28** (−.30**)	.03 (.03)
5. SRT environment-centered					–	−.54** (−.51**)	.12 (.07)
6. Spatial Orientation Test						–	.15 (.06)
7. Verbal Fluency							–

Note: Values in parentheses are the partial correlation coefficients controlling for age; SRT = spatial referencing task; $N = 114$; *$p < .01$; **$p < .001$.

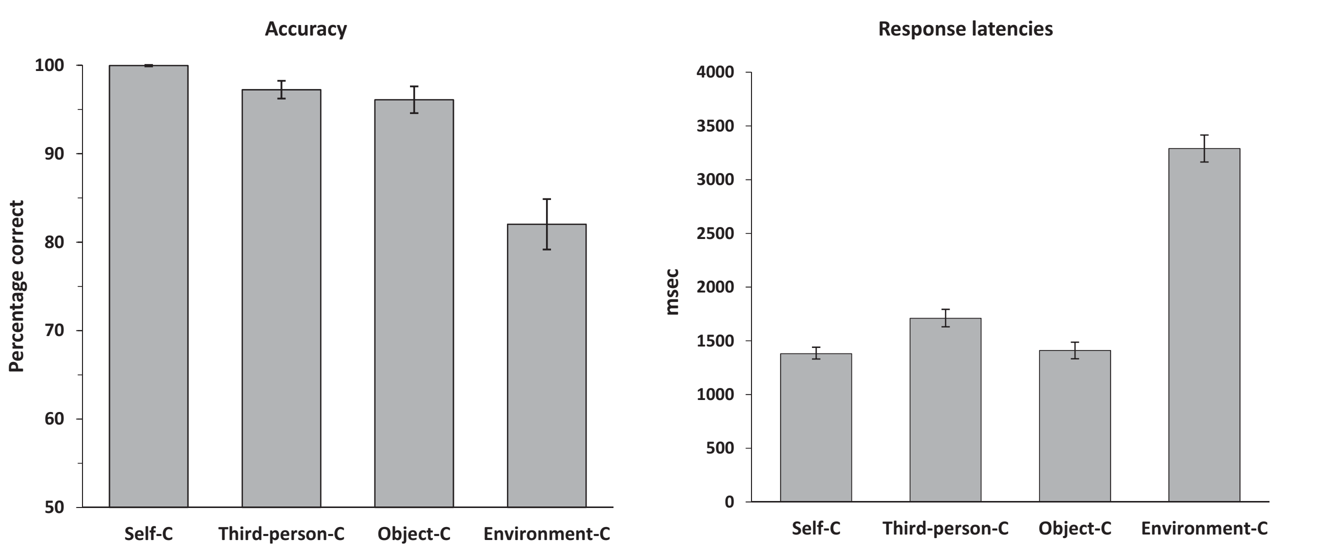

Figure 2. Performance based on accuracy (proportion of correct responses; left panel) and speed (average response latencies; right panel) under different spatial reference frames. *Note.* Error bars represent 95% confidence intervals; C = centered; $N = 160$.

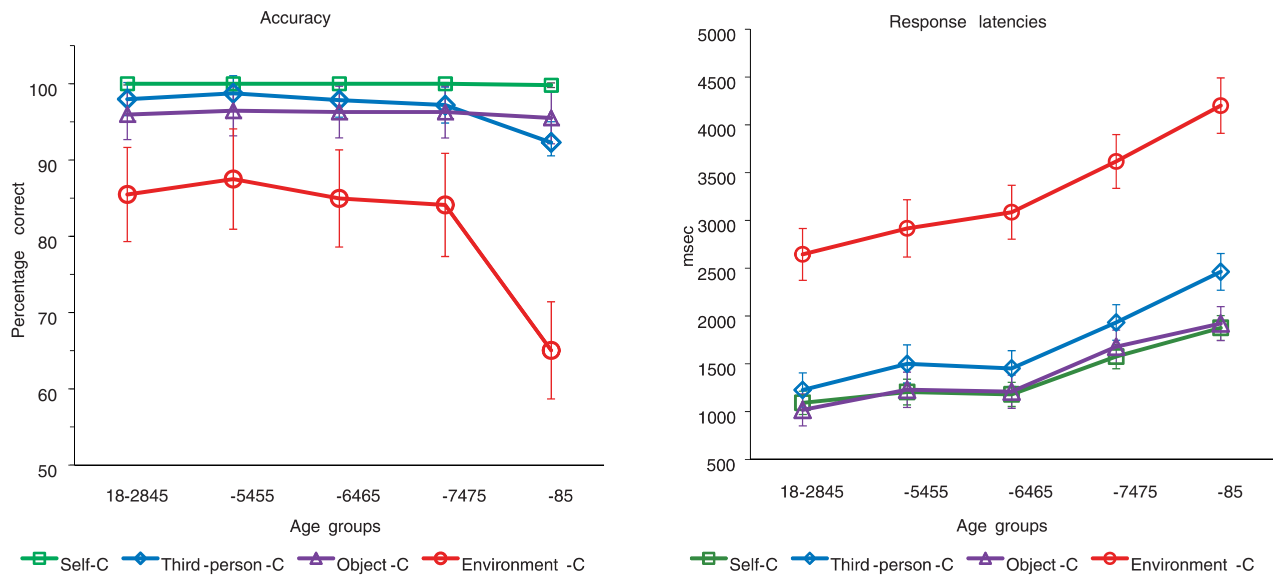

Figure 3. Performance based on accuracy (proportion of correct responses; left panel) and speed (average response latencies; right panel) under different spatial reference frames across the adult lifespan. *Note*. Error bars represent 95% confidence intervals; C = centered; N = 160.

Accuracy

There was a significant main effect of SRF, $F(3, 465) = 94.84$, $p < .001$, $\eta_p^2 = .38$ on processing accuracy. Participants, irrespective of their age, were less accurate in the environment-centered frame compared to the self-, third-person-, and object-centered frames ($p_s < .001$), while accuracy was significantly higher in the self-centered frame compared to all other SRFs ($p_s < .001$; Figure 2, left panel).

A significant main effect of age group was also found, $F(4, 155) = 8.84$, $p < .001$, $\eta_p^2 = .19$, which was qualified by a significant age group × SRF interaction, $F(12, 465) = 5.73$, $p < .001$, $\eta_p^2 = .13$ (Figure 3, left panel). Follow-up Bonferroni-corrected simple effects analyses revealed that age significantly affected accuracy performance in the third-person-centered, $F(4, 155) = 4.99$, $p = .001$, $\eta_p^2 = .11$, and environment-centered, $F(4, 155) = 8.76$, $p < .001$, $\eta_p^2 = .18$, frames, but not in the self- and object-centered frames ($p_s > .250$). Bonferroni-corrected within group comparisons further indicated that the 75–85 age group was significantly less accurate than all other age groups in the third-person-centered SRF ($p_s \leq .012$), as well as in the environment-centered SRF, ($p_s \leq .001$; Figure 3, left panel). No other significant group differences were observed ($p_s > .250$).

Response latencies

A similar repeated measures ANOVA resulted in a significant main effect of SRF, $F(3, 465) = 920.25$, $p < .001$, $\eta_p^2 = .85$, on response latencies. Participants, irrespective of their age, were significantly slower in processing descriptions of spatial relations within the environment-centered frame compared to all other frames ($p < .001$; Figure 2, right panel). Moreover, processing speed in the third-person-centered frame was significantly slower than the speed in the self- and object-centered frames ($p < .001$), while response latencies in the self- and object-centered SRFs were at similar levels ($p > .250$; Figure 2, right panel).

A significant main effect of age group on response latencies was also found, $F(4, 155) = 34.96$, $p < .001$, $\eta_p^2 = .47$, which was qualified by a significant age group × SRF interaction effect, $F(12, 465) = 5.02$, $p < .001$, $\eta_p^2 = .12$ (Figure 3, right panel). Follow-up Bonferroni-corrected simple effects tests showed that age significantly affected response latencies across all SRFs (self-centered: $F(4, 155) = 30.58$, $p < .001$, $\eta_p^2 = .44$; third-person-centered: $F(4, 155) = 30.93$, $p < .001$, $\eta_p^2 = .44$; object-centered: $F(4, 155) = 21.59$, $p < .001$, $\eta_p^2 = .36$; environment-centered: $F(4, 155) = 22.74$, $p < .001$, $\eta_p^2 = .37$). Subsequent Bonferroni-corrected within group comparisons further indicated that the older 65–74 and 75–85 age groups exhibited significantly longer response latencies compared to the younger and middle-aged adults of the 18–28, 45–54, and 55–64 age groups across all SRFs ($p_s \leq .027$; Figure 3, right panel). In addition, the 75–85 age group was significantly slower compared to the 65–74 age group in the third-person-centered ($p < .001$) and environment-centered ($p = .017$) SRFs, suggesting an accelerated decline in the speed of processing spatial relations across these frames in late adulthood, which is also manifested by the non-parallel slopes of lines for these frames compared to the self- and object-centered frames in Figure 3 (right panel).

Correlation and mediation analysis with executive functioning measures

Correlations

Table 5 shows bivariate correlations among speed and accuracy measures of the SRT and the executive functioning measures. Overall, there were modest negative correlations between response latencies and accuracy scores, suggesting that slower processing speed was less likely to result in accurate responses. Moreover, all executive functioning measures were found to significantly correlate with both SRT accuracy and speed scores, indicating that individuals

Table 5. Bivariate correlations between all accuracy (proportion of correct responses) and speed (average response latencies) scores in the Spatial Referencing Task and executive functioning measures.

Measure	1	2	3	4	5	6	7	8	9	10	11	12	13
1. SRT: Composite accuracy	–	−.62**	−.02	−.49**	.51**	−.61**	.55**	−.51**	.87**	−.61**	.36**	−.45**	.31**
2. SRT: Composite speed		–	−.04	.89**	−.30**	.92**	−.31**	.89**	−.56**	.92**	−.45**	.56**	−.57**
3. Self-centered: Accuracy			–	−.08	.04	−.02	.03	.02	−.05	−.06	−.05	.04	−.04
4. Self-centered: Speed				–	−.25*	.81**	−.21*	.82**	−.45**	.73**	−.38**	.53**	−.54**
5. Third-person-centered: Accuracy					–	−.38**	.28**	−.20*	.19*	−.25**	.18*	−.25**	.13
6. Third-person-centered: Speed						–	−.26**	.76**	−.54**	.79**	−.43**	.54**	−.56**
7. Object-centered: Accuracy							–	−.43**	.17*	−.22**	.07	−.07	.07
8. Object-centered: Speed								–	−.39**	.72**	−.35**	.48**	−.46**
9. Environment-centered: Accuracy									–	−.60**	.37**	−.46**	.33**
10. Environment-centered: Speed										–	−.45**	.50**	−.51**
11. Visuospatial working memory											–	−.45**	.47**
12. Mental flexibility												–	−.59**
13. Inhibitory control													–

Note: $N = 160$; *$p < .05$; **$p < .001$.

with higher spatial working memory capacity, stronger mental flexibility, and higher inhibitory control were faster and more accurate in processing spatial relations across the different SRFs. However, the correlations between inhibition and SRT accuracy scores were marginal.

Mediation models

Next, we employed a series of mediation regression models with Preacher and Haye's (2008) bias-corrected bootstrapping procedure for models with multiple mediators (based on 1,000 bootstrap resamples) to examine whether executive functions account for the age effects on spatial processing in each SRF. These models simultaneously examined direct and indirect age effects whereby age predicted each of the three putative executive functions which in turn predicted spatial processing. Age was entered as a continouous variable.

Self-Centered SRF. The first model showed no significant direct or indirect effects of age on self-centered processing accuracy. In a separate model for response latencies, age remained a significant predictor of self-centered processing speed when executive functions were taken into account, while no indirect age effects through executive functions were revealed (mental flexibility: *ab* = .11, 95% BCa CI [−.01 to .21]; inhibitory control: *ab* = .08, 95% BCa CI [−.06 to .22]; visuospatial working memory: *ab* = .02, 95% BCa CI [−.04 to .09]).

Third-Person-Centered SRF. The analysis showed that age no longer predicted third-person-centered processing accuracy when performance on the executive functioning tasks was taken into account (Figure 4A). The model revealed an indirect effect of age on processsing accuracy through mental flexibility, *ab* = −.11, 95% BCa CI [−.21 to −.01], but not through inhibitory control, *ab* = .10, 95% BCa CI [−.03 to .24], or visuospatial working memory, *ab* = −.03, 95% BCa CI [−.09 to .02]. Regarding response latencies, results of a separate model (Figure 4B) showed that age predicted third-person-centered processing speed when executive functions were taken into account, although it was reduced. In addition, there was also an indirect effect of age on processing speed through mental flexibility, *ab* = .13, 95% BCa CI [.06 to .21], but not through inhibitory control, *ab* = .08, 95% BCa CI [−.04 to .20], or visuospatial working memory, *ab* = .04, 95% BCa CI [−.01 to .10].

Object-Centered SRF. No significant direct or indirect effects of age on object-centered processing accuracy were found (Figure 5A; mental flexibility: *ab* = −.01, 95% BCa CI [−.11 to .04]; inhibitory control: *ab* = −.06, 95% BCa CI [−.20 to .08]; visuospatial working memory: *ab* = −.02, 95% BCa CI [−.08 to .03]). However, the analysis for response latencies showed that age remained a significant predictor of processing speed when executive functions were taken into account (Figure 5B). An indirect age effect through mental flexibility was also revealed, *ab* = .13, 95% BCa CI [.06 to .21], but not through inhibitory control, *ab* = .01, 95% BCa CI [−.13 to .15], or visuospatial working memory, *ab* = .02, 95% BCa CI [−.04 to .09].

Environment-Centered SRF. The results for spatial processing within the environment-centered SRF showed that age no longer predicted accuracy when executive functions were taken into account (Figure 6A). The analysis revealed significant indirect effects of age on processing accuracy through mental flexibility, *ab* = −.17, 95% BCa CI [−.28 to −.06], and through visuospatial working memory, *ab* = −.10, 95% BCa CI [−.18 to −.02], but no through inhibition, *ab* = −.03, 95% BCa CI [−.18 to .11]. With respect to response latencies, a separate model showed that age remained a significant predictor of processing speed when performance on executive functions was taken into account (Figure 6B). Significant indirect effects of age through mental flexibility, *ab* = .11, 95% BCa CI [.03 to .19], and through visuospatial working memory, *ab* = .08, 95% BCa CI [.01 to .15], were also revealed, but no through inhibition, *ab* = .05, 95% BCa CI [−.07 to .18].

Discussion

Spatial relations between objects in the physical environment can be encoded and communicated based on different frames of reference. Several studies have found age-related impairments in allocentric spatial processing across navigation and memory paradigms (Colombo et al., 2017), as well as in third-person-centered visual perspective taking (e.g.,

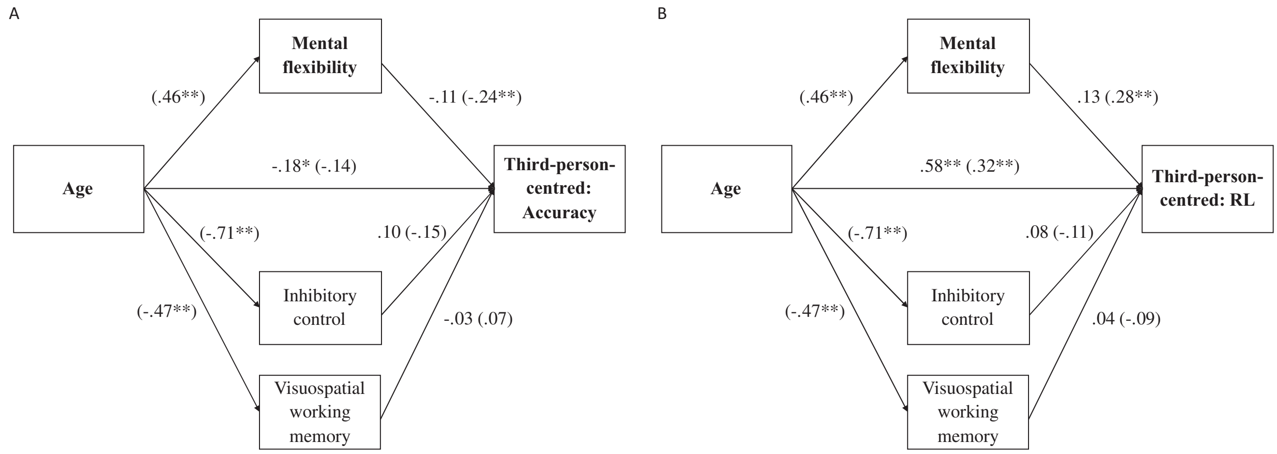

Figure 4. Path diagrams showing the effect of age on third-person-centered spatial processing accuracy (panel A) and response latencies (panel B) as mediated through the putative executive functions of mental flexibility, inhibitory control, and visuospatial working memory. *Note*. All scores are standardized beta weights. The direct effects between variables are presented in parentheses; RL = response latencies; $^*p < .05$; $^{**}p < .01$.

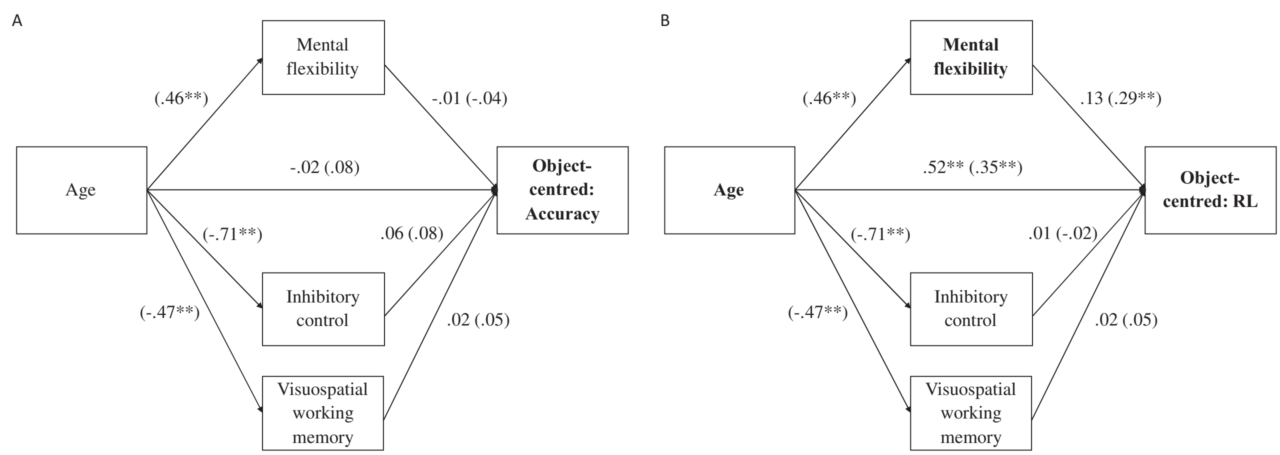

Figure 5. Path diagrams showing the effect of age on object -centered spatial processing accuracy (panel A) and response latencies (panel B) as mediated through the putative executive functions of mental flexibility, inhibitory control, and visuospatial working memory. *Note*. All scores are standardized beta weights. The direct effects between variables are presented in parentheses; RL = response latencies; $^*p < .05$; $^{**}p < .01$.

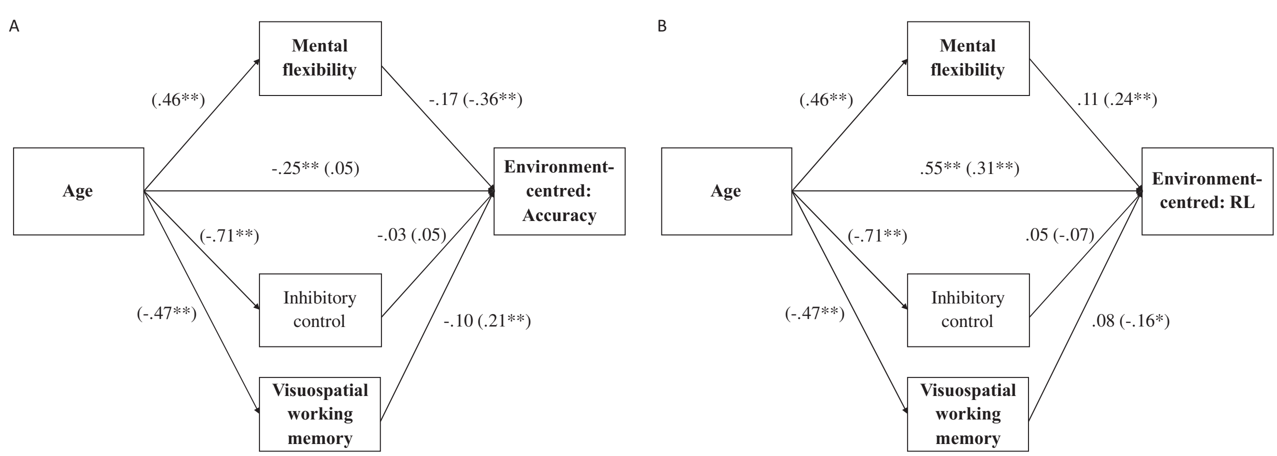

Figure 6. Path diagrams showing the effect of age on environment-centered spatial processing accuracy (panel A) and response latencies (panel B) as mediated through the putative executive functions of mental flexibility, inhibitory control, and visuospatial working memory. *Note*. All scores are standardized beta weights. The direct effects between variables are presented in parentheses; RL = response latencies; $^*p < .05$; $^{**}p < .01$.

Long et al., 2018; Mattan et al., 2017). However, there have not been previous studies examining age effects on third-person-centered spatial perspective taking, and age-related changes in spatial processing within different SRFs have been examined sparsely in the same paradigm (Montefinese et al., 2015). Consequently, the primary purpose of the present study was to examine the effects of aging on spatial processing within different SRFs from an adult-lifespan perspective. To this end, we developed a novel task, the Spatial Referencing Task (SRT), involving self-, third-person-, object-, and environment-centered judgements of projective spatial descriptions between two objects, and established its test-retest reliability and concurrent and divergent validity. Another objective was to investigate the relationship between different aspects of executive functions (working memory, inhibitory control, and mental flexibility) and spatial processing within different SRFs and whether and to what extent these domain-general executive resources explain age-related changes in this ability. Below, we summarize the results and discuss their theoretical and practical implications for spatial cognition and aging. Then, we consider the role of executive functions in spatial processing within different SRFs with a view toward building upon the most recent and relevant research. Finally, we present the strengths and limitations of this study.

Effects of SRF and aging

The first significant finding was that, overall, people's ability to process descriptions of spatial relations depended on the SRF involved. In line with our predictions, we found increased difficulty in processing spatial relations across all non-egocentric frames, which was manifested by lower accuracy scores and/or higher response latencies across the third-person-, object-, and environment-centered SRFs compared to the self-centered frame. This result highlights the cognitive difficulty of adapting to a spatial system which is different from one's own viewpoint of the world. Overall, these findings converge in favor of the "dominance" of a self-centered viewpoint in representing spatial relations and are in line with previous findings of egocentrism in spatial-perspective taking tasks (Surtees & Apperly, 2012). More broadly, these findings are also consistent with egocentric-default theories of language processing and social cognition in conceptual perspective-taking paradigms (Lin et al., 2010) and a general self-prioritizing processing bias in cognition (Cunningham & Turk, 2017). Despite an egocentric precedence in spatial processing, however, the participants in our study performed well above chance levels across all frames examined, confirming that spatial relations can be efficiently represented with respect to different SRFs (Carlson, 1999; Coventry et al., 2018; Levinson, 2003). In fact, distributions of accuracy scores in the SRT were negatively skewed, indicating that the left tail of the distributions was heavier and elongated compared to the right tail, especially in the object- and third-person-centered frames.

With respect to age differences, results showed that the impact of aging on spatial processing accuracy and speed was subject to the SRF involved. Specifically, we found no age effects on the egocentric and object-centered spatial description judgements, indicating that processing spatial relations from an egocentric viewpoint and processing binary spatial relations relative to the intrinsic orientation of the reference object remain intact throughout the adult-lifespan. By contrast, there was a mild but significant decline in processing spatial descriptions from a third-person-centered perspective and a steep decline in environment-centered spatial processing in late adulthood. These results provide new evidence for divergent, SRF-specific, aging trajectories of processing spatial relations, suggesting that the underlying operations involved in each SRF and their neural underpinnings are disproportionately affected by increasing age. This is an important finding because it is not always clear which visuospatial processes are affected by aging, when they are affected, and to what extent, and which processes are spared (Colombo et al., 2017; Klencklen et al., 2012), which can lead to diagnostic uncertainty during clinical neuropsychological assessment of older adults (Kvavilashvili et al., 2020).

While the impact of aging on spatial processing across diverse SRFs has not been thoroughly investigated, previous studies have demonstrated deficits in Level-1 visual perspective-taking, i.e., whether objects are visible from imagined perspectives, during interactive discourse (Long et al., 2018) and in perceptual matching tasks (Mattan et al., 2017) among older adults. The results of the present study extend these recent findings by demonstrating for the first time a significant age-related decline in Level-2 perspective-taking, i.e., processing how objects are spatially related to each other with respect to another person's perspective. Our findings are also in line with previous reports of age-dependent declines in spatial perspective-taking performance in block-reconstruction (Inagaki et al., 2002; McDonald & Stuart-Hamilton, 2002) and pointing (Borella et al., 2014; Zancada-Menendez et al., 2016) tasks, although those studies reported age-related declines at a younger age compared to our results. This could reflect differences in task difficulty, as the SOT and the 3MT have been previously described as difficult tasks that yield floor effects (Inagaki et al., 2002; Zancada-Menendez et al., 2016). By contrast, no floor effects were observed in the SRT. In addition, past evidence has shown that locating objects from imagined perspectives is consistently slower and less accurate when participants have to point to target objects than when they respond verbally using spatial terms to describe their locations, with much larger proportions of egocentric errors for pointing than for spatial labeling responses (Avraamides et al., 2007). This latter finding might reflect a greater egocentric processing bias attached to physical action responses, such as pointing or walking toward the relative location of an object, compared to using appropriate spatial terms to describe them.

We also found that participants of all age groups, and particularly those in their 70 s and 80 s, were substantially slower and less accurate in processing spatial relations within the environment-centered SRF, confirming an increased difficulty in representing how two objects are spatially related relative to an external environmental point. The present results are in agreement with reports of increased difficulties in forming environmental representations among older adults (Hilton et al., 2021; Markostamou & Coventry, 2021; Muffato et al., 2019, 2020) and impaired allocentric processing in large-scale environments (e.g., Harris et al., 2012; Rodgers et al., 2012; Wiener et al., 2013). Differences between spatial processing within an environment-centered SRF and other allocentric SRFs may be attributed to the cognitive costs associated with developing and maintaining an enduring representation of the broader environmental layout (Galati et al., 2010), although differences in scale might also play a role (Herweg & Kahana, 2018), as environment-centered processing typically involves larger spatial scales and longer distance estimations.

Another important finding was that although participants were overall less accurate in object-centered spatial judgements compared to egocentric processing, no significant effects of age were found in object-centered processing accuracy. The apparent discrepancy between environment-centered and object-centered spatial processing in older adults replicates results of a greater age-related vulnerability of environment-centered spatial coding compared to object-centered processing in memory paradigms (Montefinese et al., 2015). This difference could be attributed to dissociable age-related susceptibility of the different brain networks supporting spatial processing across SRFs. More specifically, when object locations are encoded relative to a fixed environmental point, medial temporal and retrosplenial regions are recruited together with parietal subregions like the precuneus, while lateral occipital-temporal areas seem to specialize for object-centered spatial processing (Committeri et al., 2004; Galati et al., 2010; Sulpizio et al., 2013). Allocentric visuospatial processing based on external environmental points and landmark localization selectively relies on posterior hippocampal and retrosplenial regions (Galati et al., 2010; Mitchell et al., 2018; Sulpizio et al., 2013), so age-related environment-centered deficits may arise from neuronal alterations, as these structures are particularly vulnerable to aging processes (Konishi & Bohbot, 2013; Ramanoël et al., 2019). Although it is highly likely that spatial representations from different SRFs closely interact to support effective spatial processing, the present findings from a lifespan sample corroborate the evidence from neuropsychological (e.g., Medina et al., 2009) and neuroimaging (e.g., Committeri et al., 2004; Marchette et al., 2014) studies which had previously demonstrated a neural dissociation among these representational systems.

The role of executive functions

As discussed earlier, the observed SRF effects on the chronometric and accuracy scores indicate that adapting to a non-egocentric spatial frame of reference is an effortful and cognitively demanding process, especially for older adults. Spatial processing based on different SRFs is thought to employ spatial viewpoint mental transformations (Michelon & Zacks, 2006), thus, one can logically expect that efficient spatial performance requires expending effortful processing resources. Accordingly, we investigated the relation between executive functioning measures, including visuospatial working memory (assessed by the Corsi blocks task), mental flexibility (assessed by the Trail Making Test), and inhibition control (assessed by the Stroop task), and SRT performance. Our correlational results overall yielded significant associations between the executive functions and SRT performance. Specifically, we found that individuals with higher visuospatial working memory capacity, stronger inhibitory control, and higher mental flexibility were likely to process spatial relations faster than those with poorer executive functioning abilities across all SRFs considered. Moreover, individuals with poorer executive functioning abilities were likely to produce a higher number of errors in third-person- and environment-centered judgements of spatial relations compared to those with higher executive functions.

More importantly, analyses with mediation models revealed significant indirect paths across the non-egocentric SRFs, whereby age-related changes in executive functions accounted for the observed changes in allocentric spatial processing. Specifically, age-related changes in mental flexibility accounted for third-person-centered processing accuracy and speed, as well as object-centered processing speed. In addition, age-related changes in mental flexibility and visuospatial working memory accounted for the variance in environment-centered processing accuracy and speed. Taken together, these findings are in line with the hypothesis that domain-general control resources play an important role in processing spatial relations within different reference frames and have a strong mediating effect on age-related variation in spatial processing.

Our results demonstrate that working memory capacity, in the form of actively maintaining and manipulating visuospatial information, is closely associated with how accurately and/or how fast people process spatial relations based on different SRFs, especially within an environment-centered frame, even when the spatially related objects are perceptually available rather than retrieved. This is consistent with the notion that limitations in working memory resources influence visual perception and encoding precision of visuospatial information (Bays et al., 2009; Van den Berg et al., 2012). In fact, previous research has proposed that the main difficulty in taking another person's visual perspective is maintaining an imagined perspective in working memory (Avraamides et al., 2015). In descriptions of projective spatial relations, SRF selection has been found to be accompanied by inhibition of the non-selected frames, as multiple SRFs may be simultaneously activated (Carlson & Van Deman, 2008). In the present study, greater inhibitory control ability was associated with faster spatial processing across all SRFs. However, inhibitory control had a weak relationship with third-person- and object-centered accuracy scores and correlated weakly with environment-centered processing accuracy. Moreover, despite the large age effects on inhibition, inhibitory control did not mediate the age-related variance in SRT performance. At first glance, these findings may seem surprising, as prior research has suggested that individual differences in inhibitory control may modulate visual perspective-taking (Brown-Schmidt, 2009; Long et al., 2018; Qureshi et al., 2010; Wardlow, 2013). However, this discrepancy is likely to be attributable to the differences in the perspective-taking task requirements. In the past reports, inhibition was found important in managing and selecting perspective-appropriate interpretations of spatial ambiguities during online discourse and simultaneously inhibiting perspective-inappropriate explanations (Brown-Schmidt, 2009; Qureshi et al., 2010). By contrast, in our study participants had to flexibly adapt to, rather than select, a given SRF, in the absence of any ambiguities.

We hypothesized that spatial processing in different SRFs would require being mentally flexible enough to switch from a self-centered viewpoint to a different way of experiencing the world. In support of this hypothesis, we found significant correlations between mental flexibility and third-person- and environment-centered processing of spatial relations. It was also revealed that the age-related decline in third-person- and environment-centered processing appears largely to be the result of age-dependent executive limitations in mental flexibility. This indicates that older adults' poorer set shifting skills modulate their perspective-taking abilities, resulting in a perseveration-like difficulty to disengage from an egocentric viewpoint of the world.

Interestingly, there exists correlational evidence suggesting that different kinds of perspective-taking abilities, such as social/affective and visuospatial, are related (Erle & Topolinski, 2017). This relation is also supported by fMRI evidence indicating that visual perspective-taking and theory of mind engage overlapping brain regions (Schurz et al., 2013). Previous research has shown that older adults exhibit deficits in their ability to represent others' mental states, especially in more complex tasks like moral judgments, which are at least partly mediated by impairments in executive functions (Charlton et al., 2009; Moran, 2013). Combined with those earlier results, the present findings corroborate the notion of an age-related decline in general fluid meta-representational abilities that span from social to visuospatial perspective-taking paradigms, which appears to be largely accounted for by age-related changes in domain-general executive functions.

Strengths, limitations, and future directions

One of the main strengths of the current study is that it simultaneously examined and compared how people process the same spatial relations between objects across different SRFs, as opposed to previous investigations which had typically focused on one frame. Another strength is that it examined inhibition, mental flexibility, and working memory capacity, allowing us to gain a more comprehensive understanding of the role of executive functions in spatial processing under different SRFs, as well as their contributions to age-related changes. Moreover, rather than comparing two age groups representing the extremes of the adult-lifespan, we employed a cross-sectional design and followed a carefully considered recruitment protocol to cover a broad age range of younger, middle-aged, and older adults. Additional investigations that adopt similar cross-sectional as well as longitudinal designs are required to replicate the present findings and draw stronger conclusions regarding the aging effects on spatial processing from different SRFs.

A limitation of the present study is that we did not collect measures of the strategies our participants used to process the spatial relations in each SRF examined. Existing evidence suggests that successful spatial perspective-taking relies on perspective transformations that are achieved through self-based mental rotations (i.e., imaging oneself in the position of the defining spatial referent, which can be either an object or another person; Michelon & Zacks, 2006; Kessler & Rutherford, 2010). However, it is possible for people to alternatively use an object-based mental rotation strategy to solve spatial perspective-taking tasks, where they reconfigure spatial relations as they appear from their own perspective (such as employing a "flipping left and right strategy"; e.g., Gardner et al., 2013). Given the involvement of mental rotation skills in spatial perspective-taking and processing spatial relations within different SRFs and that mental rotation skills decline with increasing age (e.g., Borella et al., 2014; Markostamou & Coventry, 2022), future studies should examine whether utilization of different mental rotation strategies may explain variations in spatial performance across the different SRFs and whether spontaneous strategy use changes with increasing age.

Another limitation is that we did not manipulate the degree of perspective change (i.e., the angular disparity between the participant's self-centered and the target perspective) in the different SRFs examined. In our paradigm, the angular disparities in the third-person- and object-centered frames were canonical/orthogonal, whereas in the environment-centered frame the disparity was non-orthogonal. Previous research has revealed a significant association between angular disparity and performance in object-centered spatial memory (Mou & McNamara, 2002) and pointing (Zancada-Menendez et al., 2016) tasks, as well as in third-person-centered perspective-taking (Kessler & Thomson, 2010; Zacks & Michelon, 2005), with decreased speed and/or lower accuracy in non-orthogonal angular disparities. It is possible that this non-orthogonal angular disparity in the environment-centered condition exacerbated the observed differences between the environment-centered and the other allocentric conditions. Therefore, more systematic investigations are required to examine the role of degree perspective change in processing spatial relations across different reference frames in aging.

Conclusions

The present study resulted in several novel insights that contribute to understanding both spatial cognition and cognitive aging. First, our findings demonstrate discrepancies in processing spatial relations depending on the SRF involved. Processing spatial relations from any non-egocentric perspective was more demanding than self-centered spatial processing, as evidenced from accuracy rates and response latencies. Second, the impact of aging on processing spatial relations was subject to the SRF involved, with self- and object-centered processing remaining intact throughout the adult-lifespan and third-person- and environment-centered processing declining in late adulthood. Together, these findings highlight the diversity of spatial processing abilities depending on the SRF considered and suggest that different SRFs are supported at least partially by dissociable neural substrates which are varyingly sensitive to aging. Third, the current study confirmed the importance of domain-general control abilities in spatial relations processing across different SRFs, indicating that people's ability to adapt to a different SRF depends on their capacity to employ effortful cognitive resources, especially mental flexibility and working memory resources. It was also found that age-related declines in spatial processing within different SRFs are largely dependent on executive functioning limitations associated with aging, especially in mental flexibility and visuospatial working memory capacity.

These insights are important if we consider how often people are required to be able to shift from a self-centered viewpoint of the world and mentally reorganize visuospatial representations according to a different, exocentric reference frame. Finally, another contribution of thepresent study is the development of the SRT, which affords objective assessment of visuospatial processing within different SRFs. Our data demonstrated excellent test-retest reliability of the SRT and no practice effects on accuracy scores, indicating that it provides consistent results over time, as well as good evidence of construct validity. This brief and simple task can provide a useful means of visuospatial assessments in future experimental and clinical investigations.

Disclosure statement

The authors report there are no competing interests to declare.

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Data availability statement

The data that support the findings of this study are openly available in OSF at https://osf.io/9kuy8/.

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