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Learning in the navigational space: Age differences in a short-term memory for objects task

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ABSTRACT

Age differences during development in visuospatial short-term memory (VSTM) in navigation have not been sufficiently proven. The performance of typically developing children from five age groups (from 5 to 9 years old) and one group of young adults (from 25 to 30 years old) was studied in an Augmented Reality navigational VSTM task that involved remembering the location of objects presented in increasing span lengths. The main results showed that navigational VSTM has not fully developed at the age of 9. The measures of performance significantly improved between ages 8 and 9. The overall performance on our navigational task was not influenced by gender, but there was a slight advantage for males when the difficulty of the task increased regarding the performance accuracy and the errors committed. The Augmented Reality task correlated with traditional spatial tests. Possible cognitive, biological, and methodological explanations for the findings are discussed.

1. Introduction

Topographic memory is the capability to remember physical and spatial features of environments. The mental representation of the environment depends on distinct brain substrates that are based on the kind of space that is coded (i.e., body, near or far space) (Marshall & Fink, 2001; Nemmi, Boccia, Piccardi, Galati, & Guariglia, 2013; Rizzolatti, Berti, & Gallese, 2000). Consequently, the brain representation of the body or personal space involves the physical body structure; the representation of the near or peripersonal space refers to the physical environment within reaching distance; and the representation of the far or extrapersonal space refers to the outside reaching distance, which is often referred to as the navigational space.

Much of human behaviour takes place in the navigational space, which includes different activities that we do while walking through an environment (e.g., searching for or locating objects, finding the way back to a room, and learning a route). The space can be processed and represented using two reference frames (Burgess, 2006): navigation related to the use of self-movement and internal cues, which is based on the egocentric reference frame; and navigation using external cues, which is based on the allocentric reference frame. Allocentric navigation uses mapping or geometrical calculations to locate places, whereas egocentric navigation is guided by one's body position in space. Egocentric and allocentric reference frames are encoded in different brain systems (reviewed in Knierim & Hamilton, 2011). Hence, when the ability to navigate through the environment is impaired after brain damage, the consequences severely affect the person's daily functioning (Bouwmeester, van de Wege, Haaxma, & Snoek, 2015; Ruggiero, Frassinetti, Iavarone, & Iachini, 2014).

With regard to the impairment in navigational competencies, this type of deficit could appear during development in a selective disorder called developmental topographical disorientation (Bianchini et al., 2010, 2014; Iaria & Barton, 2010; Iaria, Bogod, Fox, & Barton, 2009). This disorder is characterized by impairment in spatial orientation skills but with no evident neurological or psychiatric disorders. The difficulties appear in early childhood, but the awareness of these difficulties arises in adolescence.

Furthermore, apart from the existence of specific developmental navigational disorder, children with poor spatial abilities are considered more likely to have learning difficulties that are associated with poor academic outcomes. The principal kind of spatial test that is related to academic performance is short-term memory for visuospatial information (Alloway & Alloway, 2010). Thus, for example, Rourke (1993) described that children with learning disabilities had spatial-related deficits on a variety of specialized tests. Specifically, these spatial deficits have also been associated with non-verbal learning disability (Mammarella &

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Cornoldi, 2014; Mammarella, Giofrè, Ferrara, & Cornoldi, 2013), dyscalculia (Szucs, Devine, Soltesz, Nobes, & Gabriel, 2013) and specific language impairment (Bavin, Wilson, Maruff, & Sleeman, 2005).

Visuospatial short-term memory (VSTM) refers to the capacity to hold a small amount of information in mind in an active state for a short period of time. Logie's model considers VSTM to be a storage component that is composed of separate processing parts: the visual cache and the inner scribe (Logie, 1995, 2003). The visual cache temporarily stores static visual information and the inner scribe deals with spatial and movement information, providing a mechanism whereby visual information can be subjected to rehearsal and transferred to the central executive system. Research regarding the temporary storage of visual and spatial information in the peripersonal space suggests that variations in the type and number of visual and spatial items to be remembered are relevant in determining which cognitive processes are involved and, consequently, the differences found in performance (e.g., Cowan, Naveh-Benjamin, et al., 2006; Logie & Pearson, 1997; Zimmer, Speiser, & Seidler, 2003). For example, clear dissociations in the memory systems involved were established between short-term memory for the location of spatial positions only and short-term memory for the spatial location of several objects that were simultaneously presented (Zimmer et al., 2003). It has been suggested that when the items to locate are objects, there is an activation of episodic memory traces based on visual records, whereas spatio-temporal marking and shifting spatial attention are involved when only positions are to be located (Zimmer et al., 2003). Thus, some skills are more likely to be effective than others in the solution of a specific VSTM task. For example, verbal skills are important for the association between spatial locations and objects (Cowan, Saults, & Morey, 2006). Also, greater cognitive effort is needed to solve tasks where this type of association is promoted (Cowan, Naveh-Benjamin et al., 2006). In addition, Wang and Carr (2014) suggested that the verbal working memory ability is related to analytic strategies for solving spatial tasks.

It is worthy to note that the vast majority of tests for the assessment of VSTM do not involve the participant's movement through the environment. The traditional procedures consist of static tasks with artificial stimuli that the person completes while sitting in a chair (e.g., Alloway, 2012; Boringa et al., 2001; Kessels, van Zandvoort, Postma, Kappelle, & de Haan, 2000; Reynolds & Bigler, 2001). To our knowledge, the Walking Corsi Test (WCT) of Piccardi et al. (2008) is the first visuospatial short-term memory task developed that involves the movement of the person in order to recall sequences of steps that correspond to different spatial locations of the navigational space. This task was designed as a modified version of the Corsi Block-Tapping Test (Corsi, 1972). The WCT has demonstrated that spatial processing is different when the navigational space is considered in the assessment procedure, involving differences in the strategies used and the memory systems engaged (Piccardi et al., 2010; Piccardi, Bianchini et al., 2014; Piccardi, Iaria, Bianchini, Zompanti, & Guariglia, 2011). Later, an electronic version of the WCT supported this finding (Belmonti, Cioni, & Berthoz, 2015). More recently, an Augmented Reality (AR) task has been developed for the assessment of visuospatial short-term memory in children (ARSM task). The children gave high scores for satisfaction and usability (Juan, Mendez-Lopez, Perez-Hernandez, & Albiol-Perez, 2014). The ARSM task involves an active search for a sequence of object images, which are presented in AR and located in the real word. According to Logie's theoretical model of short-term memory, we could argue that performance on the ARSM task requires the children to retain two memory sequences (a sequence of the objects that are visually perceived and a sequence of the spatial locations that the children navigate), whereas the performance on the WCT only involves the sequence for spatial locations since the visual information on the WCT does not vary according to location (Piccardi et al., 2008).

In the area of short-term memory development, it is well established that short-term memory abilities greatly increase up to adolescence (see review of Gathercole, 1999). However, this improvement does not follow a pattern of steady growth until reaching the asymptotic level. As regards VSTM, previous research showed that the short-term memory span for visuospatial information presented in the peripersonal space steeply increased up to eight years of age, but the improvement became more gradual thereafter (Isaacs & Vargha-Khadem, 1989; Leon, Cimadevilla, & Tascon, 2014; Nichelli, Bulgheroni, & Riva, 2001; Piccardi, Palermo et al., 2014; Piccardi et al., 2014). Also, similar results were found when the navigational space was considered (Piccardi, Leonzi et al., 2014; Piccardi, Palermo et al., 2014).

Comparing two VSTM task versions, the studies conducted with typically developing children clearly showed a delay in the performance of the walking version task compared to the classical one; however, these studies also showed disparity regarding the effect of gender in the performance of children in the new version (Belmonti et al., 2015; Piccardi, Leonzi et al., 2014; Piccardi, Palermo et al., 2014). These contradictory results are in line with the inconsistent results concerning gender differences in spatial abilities that can be found in previous published data (for a review see Andreano & Cahill, 2009; Coluccia & Louse, 2004; Wang, Cohen, & Carr, 2014). The literature has focused mainly on young adults and little attention has been paid to the differences in the early ages of development (e.g., Belmonti et al., 2015; Leon et al., 2014; Mendez-Lopez, Mendez, Lopez, & Arias, 2009; Nichelli et al., 2001; Piccardi, Leonzi et al., 2014; Piccardi, Palermo et al., 2014). Leon et al. (2014) reported interesting findings regarding the developmental period. The children interacted with a virtual space using a joystick and the short-term memory performance was determined by a flexible allocentric representation of the space. The authors found that 7 and 8-year-old children were more accurate in the solution of the task when they had to remember two locations than the 6-year-olds. However, the performance was good in 6-year-olds when the memory load was limited to a single location. The performance on these trials was not influenced by gender; however, the authors did suggest that the level of difficulty of the task was a core factor for the emergence of gender differences. Therefore, it might be interesting to determine how individual differences appear in a more complex task in which the allocentric representation of the space was not facilitated. In our work, we used the ARSM task for this purpose. The ARSM task involved the retrieval of several positions (up to a maximum of 6), and there was additional information to be retained about these positions (i.e., objects). Also, correlations between performance in the ARSM task with classical visuospatial and verbal memory tests can help to reveal the cognitive factors contributing to the differences found in the performance of a memory span task for visuospatial information in the navigational space.

Therefore, we used the ARSM task as a behavioral tool to explore the children's ability to temporarily store an increasing number of associations between objects and locations (i.e., up to six). Based on observations from the literature (e.g., Contreras, Rubio, Peña, Colom, & Santacreu, 2007; Leon et al., 2014), we considered different measures derived from the ARSM task to cover many factors of performance. Specifically, we obtained the following indicators: general performance, visuospatial span, accuracy in locating the objects, performance accuracy in difficult trials and degree of accuracy in the spatial representation of the longer object-locations sequences. In addition, we also assessed the basic short-term memory capability of children in the peripersonal space. Specifically, we obtained information about the following abilities (Reynolds & Bigler, 2001): simultaneous retention of spatial items, retention of complex visual information that is presented sequentially, ability to learn locations, and delayed recall of locations learned. In addition to this, we also measured verbal short-term memory ability, since the visuospatial span was associated with the verbal span previously (Adams & Gathercole, 2000) and verbal skills influenced the performance on spatial tasks (Cowan, Saults and Morey, 2006; Wang & Carr, 2014). Based on this information, we investigated three key questions: (a) whether age and gender were factors that influence short-term memory for the object-location sequences that were presented in the