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Mental representations derived from navigation: The role of visuo-spatial abilities and working memory

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ABSTRACT

There is a growing interest in individual visuo-spatial skills and their role in environment learning from navigation because they can be key factors in explaining how navigation performance varies across individuals. The present study examined the role of visuo-spatial skills in navigation-based environment learning, focusing on rotation ability and visuo-spatial working memory (VSWM). A group of 83 females individually performed a series of visuo-spatial and verbal (control) tasks, and learned three routes through the same virtual environment. Their recall of each route (retraced in the same environment or reproduced separately in a drawing) and of the whole environment (in a drawing of all three routes and the identification of a shortcut) was assessed. Two path models were developed (using single route [Model 1] and whole environment [Model 2] recall performance as final dependent variables), inputting the rotation task as the initial predictor and VSWM between the predictor and the dependent variables. The results showed that the relationship between rotation ability and environment learning accuracy is indirect, through the intervention of VSWM. How individual visuo-spatial skills can work at different levels (as an interface and/or as a-priori abilities) is discussed.

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1. Introduction

1.1. Environment learning: navigation

Planning a route and moving through a space to a destination is an everyday spatial activity completed mainly by using navigation. This is a process by means of which a space is experienced from an egocentric point of view, based on sensorimotor information about an individual's position in space, self-to-object distances, and self-motion, which enables a sequence of landmarks, turns, and changes of direction to be acquired, and a set of place-action associations to be memorized (Montello, 2005). Navigation gives rise to mental representations (also called cognitive map, Tolman, 1948) that can be defined as flexible representations of an environment not necessarily associated with a specific orientation, where spatial relations can be inferred from any perspective (Wolbers & Hegarty, 2010). One way to explore how cognitive maps are formed from navigation is to ask people to learn a series of routes (which may be connected by crossroads or partially overlap) through the same environment and then testing their ability to integrate spatial information about the multiple routes through this environment, to identify shortcuts, for instance, or point in the direction of a given landmark, or draw a map (e.g. Foo, Warren, Duchon, & Tarr, 2005; Harris & Wolbers, 2014; Ishikawa & Montello, 2006; Wiener & Mallot, 2006). The ability to integrate spatial information in the representation of an environment depends on several external factors, such as the route's complexity (e.g. Harris & Wolbers, 2014; Wiener & Mallot, 2006), the position of landmarks (e.g. Foo et al., 2005; Wan, Wang, & Crowell, 2012), the number of repetitions of navigating actions (e.g. Ishikawa & Montello, 2006), and active versus passive navigation (e.g. Chrastil & Warren, 2013; Wan et al., 2012). Another source of variability in navigation performance stems from individual factors, such as differences in individuals' visuo-spatial skills. On this aspect, Ishikawa and Montello (2006) tested a group that learned two outdoor routes for 10 weeks (combining the two routes in the last four weeks), and they were asked to memorize the location of landmarks. Some of the participants showed no improvement in their environment learning accuracy over the weekly sessions. The authors found that the participants' different ability to represent single and combined routes correlated with differences in their individual visuo-spatial characteristics judged from participants' self-reported sense of direction.

Individual visuo-spatial skills can play an important part in explaining navigation performance (e.g. Brunyé et al., 2014; Schinazi, Nardi, Newcombe, Shipley, & Epstein, 2013; Wang, Cohen, & Carr, 2014 for a review). Although visuo-spatial abilities are recognized as being fundamentally important in everyday activities, such as academic achievement (e.g. Uttal, Miller, & Newcombe, 2013b), their contribution

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to successful navigation (considering the different visuo-spatial factors involved) has yet to be systematically explored and needs to better understood.

1.2. Environment learning: the role of visuo-spatial abilities and working memory

Different individual cognitive factors can be identified in the spatial domain, i.e. visuo-spatial cognitive abilities, and visuo-spatial processing resources such as visuo-spatial working memory (VSWM).

Visuo-spatial abilities can be defined as the skills needed to generate, retain and transform abstract visual images (Lohman, 1988). Years of research have yielded strong evidence of these skills comprising multiple, distinct factors (see Hegarty & Waller, 2006, for a review; Uttal et al., 2013a, 2013b), including rotation abilities, which have been shown to affect navigation performance. Rotation abilities based on object rotations (as measured by the Mental Rotations Test [MRT; Vandenberg & Kuse, 1978], which involves identifying 3D objects in rotated views) or on bodily rotations to view an environment from another perspective (as measured with the Perspective-Taking Task [PTT; Hegarty & Waller, 2004], which consists in imagining occupying new positions within a configuration of objects) have revealed an important role in environment learning efficiency (Blajenkova, Motes, & Kozhevnikov, 2005; Fields & Shelton, 2006; Jansen, Wiedenbauer, & Hahn, 2010; Kozhevnikov, Motes, Rasch, & Blajenkova, 2006; Weisberg, Schinazi, Newcombe, Shipley, & Epstein, 2014). For instance, Weisberg et al. (2014) asked participants to learn the location of buildings by virtually navigating along four different routes through a city, and then tested their recall of spatial information by asking them to judge the direction of buildings and to locate aerial images in a blank box. They found that participants' efficiency in these tasks correlated with their performance in individual visuo-spatial tasks, such as the MRT, OPT, and sense of direction (but not in verbal tasks).

These results show that individual visuo-spatial abilities have a direct impact on navigation efficiency. One might postulate, however, that individual visuo-spatial factors might affect navigation efficiency on different levels. In line with this assumption, in a latent factor study, Allen, Kirasic, Dobson, Long, and Beck (1996) found that the topographical knowledge acquired by navigating a route (tested with several tasks such as map placement, distance estimation) was predicted by a visuo-spatial factor (measured with a set of visuo-spatial tasks), and mediated by a sequential spatial memory factor (measured with a task that involved showing moves charting a course within a 6 × 6 matrix). matrix). This study offers an initial demonstration that spatial memory is a factor capable of intervening in the relationship between visuo-spatial abilities and environment learning accuracy. In a further study, Hegarty, Montello, Richardson, Ishikawa, and Lovelace (2006) confirmed that accuracy in navigating a route learned from direct or indirect (virtual) experience, measured with different tasks (direction and distance estimation, map drawing), was predicted directly – albeit with some differences between virtual and direct learning - by individuals' visuo-spatial ability factor (tested with the MRT, the Embedded Figures Test [Oltman, Raskin, & Witkin, 1971], and the Arrow span task, i.e. combining visuo-spatial abilities and visuo-spatial working memory), and by their self-reported sense of direction - but not by their verbal abilities. On the other hand, an indirect relationship interposing perspective-taking ability (measured using tasks based on the adoption of different positions in the environment) between visuo-spatial ability factor and navigation performance was not confirmed.

These results suggest that variables potentially intervening in the relation between visuo-spatial ability and navigating accuracy may be of a spatial nature with storing functions (Allen et al., 1996). A good candidate for this role is VSWM, i.e. the memory system devoted to maintaining and processing spatial information. On the one hand, VSWM has been found involved in processing environmental information using both indirect sources, such as maps (e.g. Coluccia & Louse, 2004) or environment descriptions (e.g. Gyselinck & Meneghetti, 2011, for a review), as well as navigation (e.g. Hund, 2016; Labate, Pazzaglia, & Hegarty, 2014; Meilinger, Knauff, & Bülthoff, 2008; Nori, Grandicelli, & Giusberti, 2009; Piccardi et al., 2015). On the other hand, VSWM shares the spatial functions involved in visuo-spatial abilities such as those implicated in rotation (Cornoldi & Mammarella, 2008; Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001).

The idea that VSWM can interconnect environment learning with visuo-spatial ability is suggested by studies showing that VSWM is involved in supporting navigation to a different extent as a function of an individual's a-priori visuo-spatial abilities. Some studies used a dual-task procedure (administering spatial, verbal or visual secondary tasks during the navigation task) to test the involvement of working memory (WM) systems in groups with good or poor spatial competences (sense of direction; Wen, Ishikawa, & Sato, 2011, 2013; or spatial preferences; Garden, Cornoldi, & Logie, 2002). Wen et al. (2011, 2013), for instance, showed that individuals with a strong sense of direction exploit all WM systems (visual, spatial and verbal) to gain configured knowledge from navigation (as tested by estimating directions or map drawing), whereas individuals with a poor sense of direction have more difficulty in forming configured knowledge using their verbal (Wen et al., 2013) or visual (Wen et al., 2011) systems alone.

These findings suggest that, thanks to its storing and processing function, WM might be able to sustain environment learning (navigation) directly, which is in turn modulated by individuals' different a-priori visuo-spatial abilities. The role of WM in mediating between visuo-spatial abilities and environment learning has not been explored directly, however. The only evidence of WM, and its visuo-spatial component in particular, being able to intervene, mediating the relationship between visuo-spatial ability and spatial learning, comes from studies using spatial descriptions (Meneghetti, De Beni, Pazzaglia, & Gyselinck, 2011; Meneghetti, Ronconi, Pazzaglia, & De Beni, 2013). Meneghetti and colleagues showed that individual visuo-spatial skills (measured with the MRT) are directly related with environment (route) learning from descriptions in which a route is described using egocentric directions (from the person's point of view), and this relation is mediated by their VSWM ability (measured with the Corsi blocks task [Corsi, 1972]). VSWM can be seen as an interface taking effect during the encoding and processing of visuo-spatial information (as in navigation), and its influence is supported by the individual's a-priori spatial (rotation) cognitive abilities.

Although a route description can resemble what happens in navigation, the two different input modalities (visual vs verbal) are likely to be associated with differences in terms of the cognitive abilities involved (such as WM [Meneghetti, Borella, Carbone, Martinelli, & De Beni, in press]). Given the lack of clear evidence of VSWM intervening between spatial (rotation) and navigation learning, this issue is investigated in the present study.

1.3. Rationale and aim of the study

This study examined how, and to what degree, spatial (rotation) abilities and VSWM affect mental representations derived from navigation.

A large group of females was first administered individual visuo-spatial measures to assess their rotation and VSWM abilities (using the MRT, the OPT and the Corsi blocks tasks). Verbal WM was also tested (using the digit span task) as a control measure (based on the assumption that verbal ability is less involved in learning from navigation; e.g. Weisberg et al., 2014). Then the group learned three routes by watching videos of a garden. Multiple recall tasks were used: after each video presentation, participants first retraced the route to consolidate what they had learned (and they were given feedback if they took a wrong direction, as in Taillade, N'Kaoua, & Sauzéon, 2016); then they drew it on paper (to ascertain whether they had learned each route); and after learning all three video paths, they had to find a shortcut, and draw a

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