The role of visuo-spatial abilities in recall of spatial descriptions: A mediation model

Chiara Meneghetti a,⁎, Rossana De Beni a, Francesca Pazzaglia a, Valerie Gyselinck b

a Department of General Psychology, University of Padua, Italy
b Université Paris Descartes, C.N.R.S., Paris, France

A R T I C L E   I N F O
Article history:
Received 31 January 2011
Received in revised form 14 July 2011
Accepted 29 July 2011

Keywords:
Visuo-spatial working memory
Mental rotation
Spatial description

A B S T R A C T
This research investigates how visuo-spatial abilities (such as mental rotation — MR — and visuo-spatial working memory — VSWM —) work together to influence the recall of environmental descriptions. We tested a mediation model in which VSWM was assumed to mediate the relationship between MR and spatial text recall. First, 120 participants were assessed for MR and working memory (both visuo-spatial and verbal) abilities. Participants then listened to spatial descriptions and performed spatial recall tasks. The expected model was verified, indicating that it is possible to define an order for how visuo-spatial abilities modulate environmental learning, with MR as a predictor and VSWM as a mediator.

© 2011 Elsevier Inc. All rights reserved.

One way of acquiring environmental knowledge is through verbal input, such as a spatial description. From this, the listener/reader forms a mental representation, a so-called spatial mental model (Johnson-Laird, 1983); this representation maintains the spatial properties of the text processed, such as relationships between objects (e.g., Taylor & Tversky, 1992). The construction of efficient spatial mental representations depends on several cognitive factors. In this study, we examine the role of visuo-spatial abilities — particularly mental rotation (MR) and visuo-spatial working memory (VSWM) — in building mental representations derived from spatial (environmental) descriptions.

Visuo-spatial abilities allow us to generate, retain, and transform abstract visual images (Lohman, 1979) and are generally distinguished into three sub-factors: spatial perception, spatial visualization, and mental rotation (for an example, see the meta-analysis of Linn & Petersen, 1985). The latter two sub-factors, consisting of the ability to perform multi-step manipulations of complex spatial information (spatial visualization) and to manipulate figures rotating 2D or 3D stimuli (mental rotation), are relevant for environmental learning. For example, Hegarty, Montello, Richardson, Ishikawa, and Lovelace (2006) used a structural equation model to show that visuo-spatial abilities (tested with spatial visualization, mental rotation, and spatial working memory tasks) and sense of direction can predict environmental learning (see also Allen, Kirasic, Dobson, Long, & Beck, 1996). In the current study, the analysis focuses on mental rotation ability, which is shown to be relevant in predicting environmental learning either alone (e.g., Fields & Shelton, 2006; Pazzaglia & De Beni, 2006) or together with other visuo-spatial abilities (e.g., Hegarty et al., 2006). In addition, this spatial ability is involved in the construction of mental representation derived from environmental descriptions (e.g., Haenggi, Kintsch, & Gernsbacher, 1995; Meneghetti, Pazzaglia, & De Beni, 2011; Pazzaglia, 2008). The latter studies typically employed an individual differences paradigm in which groups with different levels of spatial ability were compared. For example, Pazzaglia (2008) showed that high-MR individuals (tested using the Mental Rotations Test; Vandenberg & Kuse, 1978) recalled environmental descriptions presented in survey perspective (better than low-MR individuals using allocentric point of view and extrinsic frame of reference, such as compass directions), although the difference fell when the text was presented together with a map of the same environment.

Another visuo-spatial skill involved when people learn about an environment is the VSWM (as suggested by Hegarty et al., 2006). According to Baddeley’s (1986) working memory (WM) model, VSWM is a system devoted to maintaining and processing visuo-spatial information; together with verbal working memory (VWM, which maintains and processes verbal information), these two subsystems are modality-specific controlled by the central executive (CE). Clear evidence of VSWM’s involvement in spatial text processing was obtained in earlier studies using an individual differences paradigm. For example, Pazzaglia and Cornoldi (1999, Exp. 1) found that individuals with high spatial span had better spatial text recall than did their lower-ability counterparts. The spatial span was evaluated using the Corsi Blocks task (Corsi, 1972), which is typically used to assess VWM (e.g., Logie, 1995). The task consists of a series of blocks arranged irregularly on a board and participants must reproduce the sequences of increasing length tapped by the examiner, both in forward and in backward presentation order.

More recent studies have examined the involvement of WM systems in spatial text processing using a dual task paradigm. This procedure consists of performing a primary task (e.g., listening to a spatial
text) concurrently with a secondary task (e.g., spatial tapping — ST task, requiring participants to sequentially tap keys located on the board’s corners). If the secondary task competes for the same limited WM resources, performance on the primary task is poorer than it is for a single-task condition (e.g., Baddeley & Andrade, 2000; Logie, 1995). It is worth noting that Vandierendonck, Kemps, Fastame, and Szmalec (2004) in a dual task paradigm study found that the Corsi Blocks task requires the involvement of both VSWM and CE (using ST and random-interval generation as secondary tasks).

In a series of studies, recall of environmental descriptions was consistently found to be impaired by spatial (using ST) and verbal concurrent tasks, while recall of non-spatial text was impaired only by a verbal concurrent task (e.g., De Beni, Pazzaglia, Gyselinck, & Meneghetti, 2005; Meneghetti, De Beni, Gyselinck & Pazzaglia, 2011; Pazzaglia, De Beni, & Meneghetti, 2007). In the latter studies, spatial descriptions were presented in route perspective, i.e., using an egocentric point of view and intrinsic frame of reference (e.g., “to your left”, “behind you”, etc.). The use of ST specifically stresses spatial WM resources that are involved in route text processing; thus, the sequential arm movement is supposed to interfere with the character’s imagined movement along that path. Some studies showed that in route text (compared with survey text) there is a stronger involvement of VSWM (using ST as a secondary task) (Brunyé & Taylor, 2008; Pazzaglia, Meneghetti, De Beni, & Gyselinck, 2010), of CE (Brunyé & Taylor, 2008) and of spatial—sequential WM (Pazzaglia et al., 2010). These studies further suggest that the building of spatial mental representation derived from route perspective requires the involvement of both visuo-spatial WM and CE processes.

There is evidence that these visuo-spatial abilities (i.e., VSWM and MR) are related to each other. In an initial mediation model study, Miyake, Friedman, Rettinger, Shah, and Hegarty (2001) showed that VSWM tasks (including the Corsi Blocks task) were related to CE tasks, and that visuo-spatial abilities (including mental rotation tasks) required a strong involvement of CE. This indicates that VSWM is involved in storing and processing of visuo-spatial stimulus and that in some cases, such as in mental rotations tasks, additional involvement of CE is required. The forward and backward versions of the Corsi Blocks task are a good example of how VSWM and CE interact. Indeed, while the forward version – consisting of reproducing the sequence of blocks in the same presentation order – is strictly a measure of the VSWM storing component, the backward version – reproducing the blocks in the opposite order of initial presentation – measures both VSWM storing and processing functions. Some studies show that both versions measure spatial WM process (Mammarella & Cornoldi, 2005) but the backward version also requires the involvement of additional CE processes (Cornoldi & Vecchi, 2003, Vandierendonck et al., 2004).

To better understand the relationship between VSWM (using the Corsi Blocks task) and spatial ability (i.e., MR), Cornoldi and Mammarella (2008) investigated differences in the performance of the forward and backward versions of the Corsi Blocks task in individuals with high- and low-MR abilities. Results showed that two groups differed (high better than low) in the backward version but not in the forward version. This corroborates the idea that mentally rotating spatial stimuli requires a spatial-active WM process, which involves CE processes.

To date, there has been no thorough study of how these two visuo-spatial abilities (MR and VSWM) work together to process spatial descriptions. Initial evidence comes from some of our own studies (Gyselinck, Meneghetti, Pazzaglia, & De Beni, 2009; Meneghetti, Gyselinck, Pazzaglia, & De Beni, 2009) where we investigated the role played by spatial ability (selecting individuals with high- and low-MR ability) in relation to VSWM in environmental descriptions processing (i.e., listening to spatial descriptions and concurrently performing spatial or verbal tasks). Gyselinck et al. (2009) found that high-MR individuals maintained good spatial text recall during the performance of spatial and verbal secondary tasks, similar to control condition; their lower-ability counterparts, on the other hand, were affected by both concurrent tasks. Meneghetti et al. (2009) confirmed these results, although additionally high-MR individuals were found to be impaired in ST performance. Overall, these results showed that the two spatial groups involve VSWM during environmental description learning, but to different extents. It is worth noting that these latter studies used a combination of traditional individual differences and dual task paradigms. However, in the present study, we tested the relationships between these variables at a continuous level with mediation models in order to add evidence of how MR and VSWM abilities work together to process environmental descriptions.

We assumed VSWM to be involved in both MR (as suggested, for example, by Cornoldi & Mammarella, 2008) and spatial-route text processing (as suggested, for example, by De Beni et al., 2005). Only route perspective descriptions were considered, as previous studies showed strong VSWM involvement here (Brunyé & Taylor, 2008; Pazzaglia et al., 2010); VSWM could assume the role of mediator between MR and spatial text recall. The MRT, Corsi Blocks and Digit Span (Wechsler, 1981) tasks were administered to a large sample. The Digit Span was used to check the influence of VWM in spatial text recall, given that involvement of this component has already been demonstrated (e.g., De Beni et al., 2005). The same group listened twice to a spatial-route description, then performed free recall and graphical representation tasks. We then proposed a model testing the relationship between MR ability and spatial recall via VSWM mediation.

1. Method

1.1. Participants

A total of 120 (26 males and 94 females) undergraduates from the faculty of Psychology of the University of Padua voluntarily participated (mean age: 23.40 years).

1.2. Materials

1.2.1. Mental rotations test (MRT, Vandenberg & Kuse, 1978)

This test is comprised of 20 items, each presenting one 3D target figure and four possible matches (assembled cubes). The task is to find the two figures identical to the target but rotated in space (time limit: 8 min).

1.2.2. Working memory measures

The Corsi Blocks task (Corsi, 1972) consists of tapping sequences of blocks arranged irregularly on a board. The Digit Span task (Wechsler, 1981) consists of saying sequences of digits. Participants must reproduce the sequences of blocks/numbers in increasing length, in forward or backward order. In both measures, the sequence length varied from 2 to 9 blocks/digits (two sequences were used for each length).

1.2.3. Spatial descriptions

Two spatial descriptions – “Tourist Center” and “Holiday Farm” – that showed to be recalled as well (Meneghetti et al., 2009) were used. In both descriptions, which were similar in length and included 14 landmarks, a person imagines walking along a route. As they move, the landmark locations are gradually defined, using egocentric terms (e.g., “left,” “right”). The environments used in both descriptions are regular (a rectangle in “Holiday Farm” and a circle in “Tourist Center”; an initial sentence provides information on the global structure of the environment) and most of the landmarks are disposed on the boundary and in the center. The path begins and finishes at the same point (e.g., Entrance). An extract from the “Holiday Farm” is: “Imagine yourself standing in front the tall boundary walls of a holiday farm stretching over a rectangular area...You start to walk...”
from the entrance gate located in the first corner and go straight.... When you get to the end of the side you will be at the restaurant in the other corner of the holiday farm.”

1.3. Procedure

Participants first performed MRT and WM tasks; the Corsi Blocks and Digit Span tasks were administered in balanced order (first forward then backward). The experimenter presented the block/number at a rate of one per second; at the end of each sequence, participants had to reproduce it. The task was stopped when participants failed to reproduce two series of one length. Afterward, participants listened twice to one randomly assigned spatial description and performed a free recall task where they had to mention landmarks and their locations aloud (this was tape-recorded). Then, they performed a graphical representation task where they had to generate a map of the environment by writing/depicting the landmarks and their relative positions.

2. Results

2.1. Scoring

For MRT, one point was assigned when both figures were correctly identified for each item. For WM tasks, the final score corresponds to the maximum length of sequences that were correctly reproduced. For free recall, one point was given when participants named a landmark and gave a precise indication of its position. For example, one point was given when they said the precise spatial location as follows: “After the entrance, I will find the restaurant on the corner.” For graphical representation, one point was assigned when participants correctly depicted the landmark position, i.e., they gave the precise location of the landmark, preserving a correct relative distance between each other. For instance, one point was given when participants depicted the restaurant on the second corner of the first side. In both tasks, no point was given if the landmark was located/announced in the wrong position (independently from the presentation order) or omitted. Thus, a full score in both recall measures was given when all landmarks were correctly announced/disposed, preserving a correct relative distance between each other within the rectangular (in “Holiday Farm”) or circular (in “Tourist Center”) layout of the environment. The scores of both recall tasks were recorded by two independent judges and were shown to be highly correlated \((r = 0.95\) free recall and \(0.97\) graphical representation; \(p < 0.001\)); the analyses were then performed on the scores assigned by one judge (i.e., the experimenter).

2.2. The mediation model

As a first step, the Pearson correlations between variables (i.e., MRT, Corsi Blocks and Digit Span — backward and forward versions, free recall and graphical representation tasks) were carried out. Results (see Table 1) showed a positive correlation between the MRT, backward Corsi Blocks task, free recall and graphical representation tasks. However, these variables did not correlate with the Digit Span (forward and backward versions), and the forward Corsi Blocks task correlated with the backward version of the same task as well as with Digit Span.

As a second step, given this pattern of significant correlations, the mediation model tested the relation between VSWM (using the backward Corsi Blocks task), MR, and spatial text recall. Given the high correlation between free recall and graphical representation \((r = 0.72, p < 0.001\), a single recall measure (calculating summing the scores of these two tasks) was used. To test the model in which VSWM mediates the relationship between MR ability and spatial recall, we used the joint significance test recommended by MacKinnon, Lockwood, Hoffman, West, and Sheets (2002). The test requires (a) that the predictor variable (MRT) has a significant effect on the mediator (VSWM), and (b) that the mediator has a significant effect on spatial text recall after controlling for the effect of the predictor. We found (a) in the first regression model a significant effect of MRT on VSWM task performance \((\beta = 0.28, p < 0.001\); and (b) in the second regression model a significant effect of VSWM task on spatial text recall, after controlling for the effect of MRT \((\beta = 0.26, p < 0.01\). The coefficient of determination, including the effects of predictor (MRT) and mediator (VSWM) on spatial text recall was \(R^2 = 0.10\), and was shown to be significant \((F(2, 117) = 6.70, p < 0.01\). According to MacKinnon et al. (2002), the joint significance of the two models therefore confirmed the mediating role of VSWM on the relationship between MRT and spatial text recall (see Fig. 1).

It should be noted that the direct effect of MRT on spatial text recall is significant \((\beta = 0.21, p < 0.01)\) and that the same relation tested after controlling for VSWM measure (the mediator) became unreliable \((\beta = 0.14, p = n.s.)\). These relationships are essential for testing the effect of mediation using the Sobel test (Baron & Kenny, 1986), which proved to be significant \((z = 2.05, p < 0.05)\). Both the procedures of MacKinnon et al. (2002) and Baron and Kenny (1986) confirmed the mediation role of the VSWM task between MRT and spatial text recall. As a control, two mediation models separately considering the two recall measures (i.e., free recall and graphical representation) were carried out. Results using the two procedures were consistent, although the effects were stronger in the free recall than in the graphical representation (MacKinnon et al. 2002). Free recall: model b – \(b = 0.24, p < 0.01\); Graphical representation: model b – \(b = 0.20, p < 0.05. Baron and Kenny (1986)\). Free recall: \(z = 1.96, p = 0.05\); Graphical representation: \(z = 1.92, p = 0.06\).

Therefore, the model considering both recall measures was tested controlling for gender, because MRT and the backward Corsi Blocks task are subject to gender differences (e.g., Cornoldi & Vecchi, 2003; Linn & Petersen, 1985). The model was substantially confirmed, although with weaker coefficients, using procedures of both MacKinnon et al. (2002) (model a, \(\beta = 0.23, p < 0.05\); model b, \(\beta = 0.26, p < 0.01\); no significant gender effects \(F_{1, 117} = 0.10, F(3, 116) = 4.43, p < 0.01\) – and Baron and Kenny (1986) \(z = 1.78, p = 0.07\).

The model considering MR ability as a mediator between VSWM (the predictor) and spatial text recall also was tested. Results showed that this model satisfied the first requirement (a) i.e., significant effect of VSWM task on MRT performance \((\beta = 0.28, p < 0.001)\), but not the second requirement (b), i.e., there was no significant effect of MRT on spatial text recall after controlling for VSWM task

| Table 1 |
|---|---|---|---|---|---|---|
| **Means** | **Standard deviations** | 1 | 2 | 3 | 4 | 5 | 6 |
| 1. MRT | 7.11 | 3.77 | | | | | |
| 2. Corsi Blocks task (forward version) | 5.98 | 0.81 | 0.11 | | | | |
| 3. Corsi Blocks task (backward version) | 5.35 | 1.16 | | 0.28* | 0.03 | | |
| 4. Digit Span task (forward version) | 6.27 | 0.94 | | 0.10 | 0.14 | | |
| 5. Digit Span task (backward version) | 4.83 | 1.17 | | 0.10 | 0.19* | 0.10 | |
| 6. Free recall | 10.33 | 3.12 | | 0.21** | 0.09 | 0.28** | 0.15 |
| 7. Graphical representation | 9.91 | 3.31 | | 0.18* | 0.12 | 0.23** | 0.05 |

(one-way; *p ≤ 0.05; **p ≤ 0.01).
3. Discussion of results and conclusions

This research explored the joint influence of MR and VWM abilities on spatial text learning. Recent evidence shows that MR and VWM work together in constructing spatial mental representations derived from spatial descriptions (in route perspective) using typical individual differences (i.e., selecting individuals with high and low spatial abilities) and dual task (i.e., processing spatial description and concurrently performing spatial secondary task) paradigms (Gyselinck et al., 2009; Meneghetti et al., 2009). The novelty of this study is that it does not use the traditional paradigms and provides evidence at a continuous level of how visuo-spatial abilities (i.e., MR and VWM) influence the construction of spatial mental representation that is derived from spatial descriptions in route perspective. A mediation model was used to explore whether VWM is able to mediate the relationship between MR ability and spatial text recall. The hypothesized model was verified and showed that: (i) MR ability is related to spatial text recall (as found by previous individual differences studies e.g., Meneghetti, De Beni, et al., 2011; Meneghetti, Pazzaglia et al., 2011; Pazzaglia, 2008) and (ii) VWM (i.e., backward Corsi Blocks task — but not the forward version) is related to MR and spatial text recall. This result indicates that MR performance is supported by active spatial process of WM requiring a certain level of CE control as measured by the backward version of the Corsi Blocks task (Cornoldi & Vecchi, 2003); while MRT performance was not directly related to VWM storing component as measured by the forward version (Cornoldi & Vecchi, 2003); while MRT performance was not directly related to VSWM storing component as measured by the forward version (Cornoldi & Vecchi, 2003). Here, not only is the implication of VSWM in text processing fully supported but it also suggests that the crucial factor is the ability to process and maintain in-line spatial information allowing, for example, mental or-
learning acquired through verbal description. However, the current findings would benefit from extension through further systematic studies that are devoted to understanding whether other visuo-spatial abilities such as spatial visualization and other aspects of VSWM are involved with a precise order in the learning of environmental descriptions expressed in route perspective (as well as in survey perspective). This would allow the completion of the analysis of how different visuo-spatial abilities are involved in the construction of spatial mental representation derived from environmental descriptions.

References