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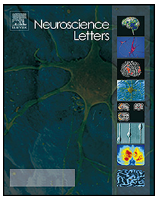

Research article

The Key of the Maze: The role of mental imagery and cognitive flexibility in navigational planning

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HIGHLIGHTS

- Key Search Task (KST) and Porteus Maze Test (PMT) require navigational skills.
- Good planners at the KST are better in reaching the exit at the PMT.
- Mental imagery is crucial in navigational planning.

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ABSTRACT

Spatial navigation planning ability relies on both mental imagery and cognitive flexibility. Considering the importance of planning ability in everyday life, several neuropsychological tests are used in clinical practice for its assessment, although some of these are not aimed at assessing the strategies of navigational planning. The Porteus Maze Test (PMT) and the Key Search Task (KST) require to plan a strategy in a maze and in an imagined space, respectively. To the best of our knowledge, although these two tests share some features, the relationship between them has never been explored. The purpose of the present study was to investigate, for the first time, the relationship between the PMT and the KST performances in 38 healthy subjects in order to understand the implications of this association for the assessment of spatial navigation ability. Subjects were subdivided in bad or good navigation planners on the basis of the their KST score. The results of the study have revealed a significant difference ($t = 2.35$; $p = 0.03$) in the number of errors made at the PMT by bad navigational planners (0.78 ± 0.28) and good navigational planners (0.10 ± 0.06). The first group (bad navigational planners) made more errors at the PMT than the good navigational planners (who made less errors at the PMT). This provides evidence of the possibility to use the KST and the PMT in a combined way as a new tool for the assessment of spatial navigational planning ability. Furthermore, this finding highlights the importance of mental imagery and cognitive flexibility in spatial navigation, suggesting that these functions could be the link between a good planning ability and a successful spatial navigation. In conclusion, this study suggests that an efficient navigation would not be possible without a good navigational planning ability.

1. Introduction

Spatial navigation enables humans to move through a new or familiar environment to reach a target. It requires a contribution from several processes such as memory, cognitive flexibility, mental imagery and planning [1–7]. Indeed, to successfully navigate, humans must remember their own position, those of the environmental objects and their final destination. While mental imagery enables the retrieval from memory of the previously encoded perceptual information [4,8,9] and the building of environmental mental representations [10], these processes allow the planning of how to reach a goal (and eventually how to modify this plan). Specifically, for goal-oriented navigation, humans use egocentric and/or allocentric strategies. The first one operates in relation to the body's changing orientation, while the second one operates accord-

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Abbreviations: BNP, bad navigational planners; GNP, good navigational planners; KST, Key Search Task; PMT, Porteus Maze Test.

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ing to a static external coordinate system [11]. Both strategies rely on two different spatial frames of reference, the viewer-centered and the environmental-centered, respectively, which can be both used for encoding and transforming visual-spatial images [12]. Despite being distinct skills, the allocentric and egocentric abilities are correlated [13]. Particularly, a translation process would exist between these systems which are both involved in higher-order spatial cognitive processes [14–16]. During navigation, humans can rely on just one strategy, or switch from one to another [11]. Harris et al. [11] have demonstrated that the ‘switching’ ability is fundamental for navigation and its deficiency may cause the navigation impairments observed in normal and pathological aging (see [15,17,18]). The spatial planning ability is the capacity of mentally evaluating and selecting the best solution that allows to reach a destination, among many imagined alternative actions [19,20] and it is closely interlaced with the choice of the most suitable strategy according to the environmental context. Generally, it is based on the principle of “cognitive saving”, namely the tendency of minimizing the cognitive resources to achieve a result through simple behavioral schemes [21]. The specific way in which these schemes are put together, with the aim of reaching a destination, creates a spatial strategy [22]. All these processes are underpinned by the cognitive flexibility, defined as the readiness with which the person’s concept system changes selectively according to appropriate environmental stimuli [23].

Considering that humans must constantly adapt their behavior to the current ever-changing context, a good cognitive flexibility, interpreted here as the ability of shifting between both different planning strategies and mental representations, determines a successful navigation.

Therefore, individuals with this ability could be considered both good navigational planners and efficient navigators.

Given the importance of planning ability in everyday life and the impairments that occur when it is lacking [24–27], several neuropsychological tests are used for its assessment, although they are not explicitly addressed to assess navigational planning strategies. Among these, the Porteus Maze Test (PMT) [28] and the Key Search Task (KST) [29] are non-verbal paper-and-pencil tests that require to plan a strategy in a maze or in an imagined space, respectively. The PMT, known for measuring the planning ability [30,31], consists of eight labyrinths in which participants must find the exit avoiding the blind alleys and the dead-ends. Since it is not possible to correct themselves during its execution, a successful execution of the PMT requires planning the best path before starting. Several studies have shown that the PMT is a driving ability predictor [32,33], a complex navigational behavior requiring multiple cognitive functions [34].

The KST, which assesses the ability to plan a searching strategy, consists of asking the participants to draw the route they would make to find their lost key in a given space. It enables the judgment of the efficacy of the chosen strategy. Furthermore, the KST instructions, asking to explore an imagined space, clearly require performing a spatial navigation task. Several studies have suggested that the KST could be utilized for assessing spatial navigation planning ability and spatial mental imagery [35–37]. Piccardi et al. [35] found that the KST could assess the navigational component of the mental imagery; Hunter et al. [36] have demonstrated that the imagined prospective adopted to solve the KST (first/third person) affected its execution. Considering this evidence, Carrieri et al. [37] have demonstrated a ventrolateral prefrontal cortex activation during the KST execution. This finding could be explained by the role of this cerebral area in spatial navigation planning ability [38,39]. Finally, Motta et al. [40] found that the KST, as the PMT, is a driving performance predictor.

To our knowledge, although the PMT and the KST share some features, the possible relationship between them has never been explored. For this reason, this study aimed at investigating the relationship between these tests to understand the implications that it could have to assess spatial navigation ability. Given the crucial role of planning ability in determining the efficacy of navigational skills, it was hypothesized that individuals who had a good performance at the KST (good navigation planners) would be also more proficient in the execution of the PMT (making a lower number of errors). To evaluate this hypothesis, the performances at the KST and at the PMT were compared.

2. Material and methods

2.1. Participants

Thirty-eight college students of L’Aquila University (22 males; age: 23.3 ± 3.4 y; educational level: 14.0 ± 1.5 y) were recruited. Participants completed a questionnaire in which they indicated any previous/current diseases. The inclusion criterion was no history of neurological/psychiatric diseases (including substance abuse or dependence). To assess the general cognitive level, all participants were administered Raven’s Colored Progressive Matrices [CPM: [41]]; no difficulty in clear-thinking ability emerged. According to the tenets of the latest Declaration of Helsinki, prior to the assessment and after a full explanation of the protocol and of the non-invasiveness of the study, a written informed consent was obtained from each participant. The University Ethics Committee approved this study.

2.2. Procedure

Prior to the study, participants were informed about the procedure. The study was conducted in a quiet room. Participants were asked to sit on a comfortable chair in front of the experimenter. They filled the informed consent, the permission to use their personal data and a brief medical history. Participants were assessed individually. The experimenter placed the stimuli of the CPM [41] in front of the participant and he recorded the time employed to perform them; if a participant exceeded 10 min, the experimenter stopped the test. None of the participants exceeded the time limit. Then, the labyrinths of the PMT and, finally, the KST were presented to the participants.

2.3. The PMT and the KST

The PMT [28] consists of 8 labyrinths of increasing difficulty drawn on some A4-sized pieces of paper (see Fig. 1a in Supplementary Materials). For each labyrinth, an arrow indicates the starting point. The test requires the participants to draw, with a pen, the route to find the exit of each labyrinth beginning from the starting point. Following the PMT handbook [28], each time the participant was taking a blind alley, a dead-ends, and was trying to turn back (once he/she realized that the taken path was the blind one) or tried to pass through a ‘wall’, were considered as errors. Labyrinths were presented one-by-one, and times were taken for each of them. Number of errors made by each participant were counted and utilized as indicator of the subjects’ PMT performance.

The KST, a subtest of the ‘Behavioural Assessment of the Dysexecutive Syndrome’(BADS) [29], consists of an A4-sized piece of paper with a 10 × 10 cm empty black square in the middle and a small black dot placed 5 cm below the center of the base of the square (Fig. 1b in Supplementary Materials). Participants were told to imagine that the square was a large field in which they had lost their key. They were asked to draw a line (with a marker), starting on the black dot, thus representing where they would walk to search the key being sure to find it. They only know that the lost key is somewhere in the field, but they don’t know exactly where. Following the BADS handbook [29], to evaluate the performance, five