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Research report

Cognitive correlates of spatial navigation: Associations between executive functioning and the virtual Morris Water Task

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HIGHLIGHTS

- We present associations of executive functioning with place learning and memory.
- Higher executive abilities correlated with better virtual navigation performance.
- Men and women differed in the executive abilities recruited for virtual navigation.

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ABSTRACT

Although effective spatial navigation requires memory for objects and locations, navigating a novel environment may also require considerable executive resources. The present study investigated associations between performance on the virtual Morris Water Task (vMWT), an analog version of a nonhuman spatial navigation task, and neuropsychological tests of executive functioning and spatial performance in 75 healthy young adults. More effective vMWT performance (e.g., lower latency and distance to reach hidden platform, greater distance in goal quadrant on a probe trial, fewer path intersections) was associated with better verbal fluency, set switching, response inhibition, and ability to mentally rotate objects. Findings also support a male advantage in spatial navigation, with sex moderating several associations between vMWT performance and executive abilities. Overall, we report a robust relationship between executive functioning and navigational skill, with some evidence that men and women may differentially recruit cognitive abilities when navigating a novel environment.

1. Introduction

The virtual Morris Water Task (vMWT) has been extensively used to characterize spatial learning and memory in humans [3,5,32,41,42,56,67,68,75,76]. The vMWT is an adaptation of the classic Morris Water Task [71] that is used to assess spatial learning and memory in rodents. The vMWT [5,68] requires participants to search a large pool of water to find a hidden escape platform. Proximal and distal cues are present to aid navigation.

The vMWT has been used to explore sex differences in spatial abilities [5,7,74–76,91], age-related changes in spatial learning and memory [3,27,28,32,67,68,112], and spatial learning and memory in patient populations including schizophrenia [42], major depression [24], and mild cognitive impairment [57]. However, healthy aging [29,86], schizophrenia [39,109], major depressive disorder [95], mild cognitive impairment [87,105], and Alzheimer's disease [12,21] are also associated with impairment in executive functioning, a group of cognitive control processes that coordinate human behavior. This has important implications for studies reporting poorer spatial navigation in patient populations. If higher executive functioning is important for successful performance on the vMWT, executive dysfunction, rather than a "pure" spatial learning and memory deficit, may partially account for this pattern of findings.

Given that MWT performance in rodents and humans heavily recruits the hippocampus [3,6,65,73], the vMWT has been used as a measure of hippocampus-dependent learning and memory. Hence, most studies investigating associations between neuropsychological performance and spatial navigation have focused on neuropsychological tests of learning and memory or spatial abilities [32,69]. Executive functions are especially important when

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Table 1
Demographic Information and Neuropsychological Performance.

	Men ($n = 36$)	Women ($n = 39$)	Difference
Age	21.4 (3.6)	21.8 (3.3)	$t = 0.54$
Education (years)	13.5 (1.3)	13.9 (1.1)	$t = 1.41$
Letter Fluency	39.7 (9.7)	37.6 (9.1)	$t = 0.92$
Category Fluency	22.5 (4.3)	20.2 (4.1)	$t = 2.17^{*}$
Switching Fluency Accuracy	12.4 (2.2)	12.9 (2.8)	$t = 0.87$
Tower Achievement Score	17.1 (2.6)	16.3 (2.7)	$t = 1.21$
Color-Word Interference (sec)	47.3 (8.5)	45.6 (9.3)	$t = 0.81$
Mental Rotations Test (correct)	12.2 (6.1)	8.7 (5.5)	$t = 2.65^{*}$

* $p < 0.05$.

individuals do not have a pre-existing schema for adaptive behavior in an environment [58,80]. Successful performance on spatial navigation tasks requires individuals to maintain a goal, select search strategies, monitor performance, and flexibly adapt their mental set with changing environmental demands. Despite this possible role for executive functioning in organizing behavior during the vMWT, studies directly linking spatial navigation to executive functioning are limited. In one of the first applications of virtual environment technology to study human navigation, higher latency to complete a corridor maze was associated with lower performance on Digits Backward, a measure of working memory [69]. In another study exploring extrahippocampal contributions to spatial navigation in younger and older adults, trial-by-trial performance on the vMWT was associated with cognitive tests assessing perseveration and working memory [67]. However, these studies included a limited number of tests of executive functioning and were not designed to provide a comprehensive study of the cognitive correlates of vMWT performance. To the best of our knowledge, only one study of virtual navigation to date has incorporated several measures of executive functioning [101]. However, this study examined virtual navigation in the context of aging and found that after controlling for age, the majority of associations between wayfinding errors and poorer executive functioning performance were no longer significant. Thus, there is a need for a comprehensive description of executive functioning and spatial navigation in healthy younger individuals.

Exploring the contributions of executive functioning to effective vMWT performance may expand our understanding of the cognitive processes contributing to successful spatial learning and memory. The objective of this study is to characterize the associations between vMWT performance and executive abilities measured by standardized neuropsychological tests in healthy young adults. Performing a thorough assessment of executive functioning and spatial learning and memory in a sample of younger adults eliminates the potential for age effects that may contaminate findings. In addition to standard summary measures of vMWT performance (e.g., latency, distance), we also include novel measures of path complexity, which may be a more sensitive index of spatial navigation strategy. Given the robust sex differences in spatial navigation favoring males [5,32,61,66,75–77,92], our secondary goal was to evaluate whether sex moderates the relationship between executive functions and vMWT performance.

2. Method

2.1. Participants

Thirty-nine women and 36 men (age $M = 21.6$, $SD = 3.4$) were recruited from the University of Wisconsin-Milwaukee psychology volunteer pool (Table 1). Participants were free of neurologic problems, substance abuse, or other health factors that may affect cognitive function, as indicated by self-report on a health screening questionnaire.

2.2. Materials

2.2.1. Neuropsychological testing

Participants completed a neuropsychological battery aimed to assess executive functions and spatial ability. This included: Delis-Kaplan Executive Functions System (D-KEFS) [31] Verbal Fluency Test, which measures letter fluency, category fluency, and category switching; D-KEFS Color-Word Interference Test, a measure of ability to inhibit automatic response; D-KEFS Tower Test, which measures spatial planning, ability to maintain set, and rule learning; and the Mental Rotations Test (MRT-A) [108], a 20-item test that requires participants to mentally rotate three-dimensional objects to match a target image.

2.2.2. Computer experience questionnaire

Participants completed the Computer Experience Questionnaire (CEQ; [66], which assesses frequency of computer and video game use. Participants report their computer and video game use on a 1 (never) to 7 (almost daily) scale, with higher scores reflecting more frequent use.

2.2.3. Virtual Morris Water Test (vMWT)

The vMWT was administered on a Dell IBM-compatible computer with a 19-in. monitor. The participant was seated in a chair so that the head was approximately 24 in. from the monitor. The vMWT environment was designed using Unreal Tournament 2003 (Epic Games). Participants used a joystick (Thrustmaster) to move through the environment. The vMWT was presented from a first-person perspective. Participants navigated a virtual pool of water placed inside an irregularly shaped room. Four distal objects placed around the pool served as navigation cues. All scoring of the vMWT task was fully automated, with a software program recording participants' coordinate position every 10 ms.

2.2.3.1. vMWT pretest training. Participants completed pretest training in a practice vMWT environment that was smaller than the test vMWT but otherwise similar in design and configuration. The platform location and visual objects that could serve as cues differed between the practice vMWT and test vMWT. Participants completed three practice trials of the vMWT to familiarize themselves with the joystick and movement through a virtual environment.

2.2.3.2. vMWT learning trials. Participants were placed into the vMWT environment and instructed to find a platform hidden beneath the surface of the water. When a participant “swam” over the hidden platform, it elevated above the surface of the water. Participants then had 10 s to freely scan the environment from the platform, although they were not explicitly instructed to do so. After the 10-s interval, a new trial immediately began from a different location in the pool. Participants were instructed that the platform location was in the same place on every trial and that they should try to remember it. If participants did not find the platform within three minutes, the experimenter used the joystick to move them to the platform before beginning the next trial. Participants completed nine learning trials.

Total latency and distance traveled on learning trials were used as measures of place learning. These measures were highly positively correlated with one another, $r = 0.83$, $p < 0.001$. Path intersections were calculated by counting the number of times a person's swim path crossed over a coordinate that was previously traveled in a given trial. Path retrace was calculated as a proportion of coordinate points that were traveled more than once in a given trial. More path intersections and higher path retrace represent poorer vMWT performance.