Development of a Virtual Floor Maze Test - Effects of Distal Visual Cues and Correlations With Executive Function in Healthy Adults

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***Abstract*—Virtual reality (VR) is a useful tool to assess and improve spatial navigation, a complex skill and relevant marker for progression of dementia. A fully-immersive VR system that allows the user to physically navigate in the space can provide an ecologically valid environment for early detection and remediation of cognitive and navigational deficits. The aim of this study was to develop a virtual version of the floor maze test (VR-FMT), a navigational test that requires navigating through an unfamiliar two-dimensional floor maze. With the VR-FMT, mazes of desired complexity and walls of preferred height can be built to challenge navigational ability and mask visual clues. Fifty-five healthy adults completed the FMT in three different conditions: real environment (RE), virtual environment with no walls (VE-NW), and virtual environment with walls (VE-W). In addition, they completed two neuropsychological tests, the Trail Making Test and Digit Symbol Substitution Test. Results showed that the time to complete the maze in the VE was significantly higher than in the RE. The introduction of walls increased the number of errors, the completion time, and the length of the path. Only time to exit in the VE-W correlated with results of the cognitive tests. Participants were further subdivided on the basis of their time to exit the maze in the RE, VE-NW, and VE-W (low navigational time - LNT, and high navigational time - HNT). Only when analyzing the time to exit the maze in the VE-W, the LNT group outperformed the HNT group in all cognitive tests.**

***Index Terms*—Cognition, floor maze test, gait, navigation, virtual reality.**

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I. Introduction

SPATIAL navigation is a complex and multi-component skill that involves the integration of visual, proprioceptive, and vestibular information and engages multiple cognitive processes, such as visual perception, spatial orientation, learning, and memory [1]. Two navigational reference systems based on the navigator's perspective are described, egocentric and allocentric [2]. Egocentric navigation is body centered, relies on landmarks, and is dependent on the networks in parietal lobes and caudate nuclei [3]. Allocentric navigation relies on mental spatial maps and activates brain networks including hippocampal regions [4], which are vulnerable to normal aging [2], mild cognitive impairment [5], and Alzheimer disease [6]. Four scales of space can be distinguished: figural, vista, environmental and geographical space [7]. The distinction between vista and environmental space is important in the context of spatial navigation. Vista spaces can be visually apprehended from a single location or with little exploratory movements. In contrast, environmental spaces require considerable movement [7].

Early diagnosis and identification of predictors for dementia is crucial. Spatial navigation is a cognitive ability that gets impaired early in the course of brain diseases and could be considered as a relevant marker for future clinical progress of dementias [8], [9]. Given the importance of navigational ability in everyday life and functional limitations that occur due to lack of it [1], several neuropsychological tests have been developed for its assessment [7]. Traditionally, the study of spatial skills was considered as a psychological challenge and only cognitive paper-and-pencil tests were used. Active navigational tests such as the Hidden Goal task (a human analog of the Morris Water Maze task) [10] and the Blue Velvet Arena [11] provide better ecological validity as subjects navigate physically in a real-space [2]. Another active navigational assessment with real-world applicability is the Floor Maze Test (FMT) [9], [12]. The FMT measures allocentric navigation skills by asking participants to navigate through an unfamiliar two-dimensional floor maze 12]. The performance in the FMT (i) correlates with cognitive ability and even more with executive functioning [12], [13]; (ii) is worse in patients with mild cognitive impairments when compared to those with only subjective cognitive complaints [9], [13]; and (iii) is a good predictor for future risk of pre-dementia syndromes and cognitive decline in non-demented older adults [9].

Regrettably, active navigational tests are also associated with some practical limitations. For example, in the FMT, space and time constraints may limit the maximum size of the maze, testing of alternate layouts, and fine control of maze features such as the height of the walls.

In the last decade, computer games and Virtual Reality (VR) are being increasingly used to study neuropsychology [14] and are now considered as useful tools to assess and also improve spatial navigation [2], [15], [16]. To the best of our knowledge, most previous studies that used VR for the analysis of spatial navigation were limited to in-place navigation controlled by keyboards, cursors or joypads while sitting [17]–[19], stepping in place on a balance board [20], or walking on a treadmill [21].

Recent advances in real-time tracking, display, and networking have allowed the development of commercially available, head-mounted, and fully immersive VR displays with room-scale tracking that allow users to navigate actively in large spaces. This can mimic real-space navigation in a more ecological setting while maintaining many of the advantages of VR systems. For example, a virtual version of the FMT would allow easy and fast modification of the floor plan, layout, dimensions, orientation, and features of the maze such as the height of the walls. This may help to alter: (i) the difficulty of the test, (ii) the reference frame (allocentric or egocentric) [2], [7], and (iii) the scale of space (vista or environmental) [7]. Moreover, it would allow to study the relationships between virtual and real maze, the challenge of spatial memory circuits, and how features of the maze such as distal visual clues from the walls affect performance in spatial navigation.

The aim of this study was to develop a virtual version of the floor maze test (VR-FMT). We aimed to: (i) investigate the differences in performance between similar real and virtual versions of the FMT; (ii) analyze the contributions of distal visual cues by adding walls in the virtual FMT; and (iii) explore associations between navigational skills in these three environments and performance in cognitive tests that target executive function.

We hypothesized that: (i) participants would take more time to complete the FMT in virtual environment (VE) compared to the real environment (RE) because walking in a VE results in gait modifications that can ultimately affect the time to exit the maze [22]; (ii) the introduction of walls in the VE (VE-W) would increase the completion time compared to no walls (VE-NW) because distal visual clues are important for spatial navigation and the lack of them poses a greater challenge to the spatial abilities [7]; and (iii) the performance in the VE-W condition would better correlate with results of the cognitive tests in comparison to the other conditions (RE and VE-NW) because of the increased level of complexity and difficulty that require a higher level of cognitive resources [7], [23].

II. Materials and Methods

A. Participants

Fifty-five healthy adults participated in the experiment. Subjects were informed about the research procedure and they signed a written consent approved by the Institutional Review Board of Columbia University, before participating. All participants had normal or corrected-to-normal vision. None of them reported any diagnosed disorder and all were naïve to the experimental conditions. Research assistants obtained information on demographic variables (age, sex, mass, height) and previous experience with VR headset. Fifteen participants had experienced at least once walking in VR with a headset.

B. Experimental Setup

Fig. 1 shows the experimental setup. A Matlab program was developed to build the geometry of the maze with an intuitive user interface. The maze can be built by allocating up to 16 types of blocks. Each block allows building walls in different directions and positions and can be used as a walkable, empty or target (e.g., entry and exit) block. The software allows choosing the number of blocks to insert in the maze. Once created, multiple maze plans can be saved and loaded for future uses. A Unity3D program was used to display a virtual floor maze within a VR headset (HTC VIVE). The software allows for immediate modifications of many features of the maze such as the size of the blocks and the height and width of the walls. Moreover, the software can track the location of the headset with a frequency of 90 Hz. With this capability, it is possible to record the time elapsed from entrance to successful exit from the maze, the length of the path, and the number of re-routings. Figures 1A and 1B show the Matlab interface, an example of a 8 by 8 maze built with it, and the corresponding maze rendered in Unity3D.

For this experiment, a 3.22 m × 3.68 m floor maze (Figure 1C) was constructed based on previous versions of the FMT [12]. The maze was identified using black tape laid down on beige hard floor in a well-lit room. The dimension and outline of the maze was simpler with respect to Sanders et al. [12] due to space restrictions within the room, maximum tracking area of the VR system, and the necessity to make the width of the path large enough to allow the participant to walk in it without being obstructed by the virtual walls.

The Matlab interface was used to build a virtual maze identical to the physical (real) maze in the room by using a grid of 7 by 8 blocks, with each block measuring 0.46 m × 0.46 m. The Virtual Environment (VE) was calibrated so that the virtual maze was aligned and mapped one-to-one with respect to the real maze. In VE, the path within the maze was rendered as white space, with green walls of width same as the tape and with variable heights (Figure 1). Two different wall heights were tested in this experiment: 0.02 m (no walls condition,

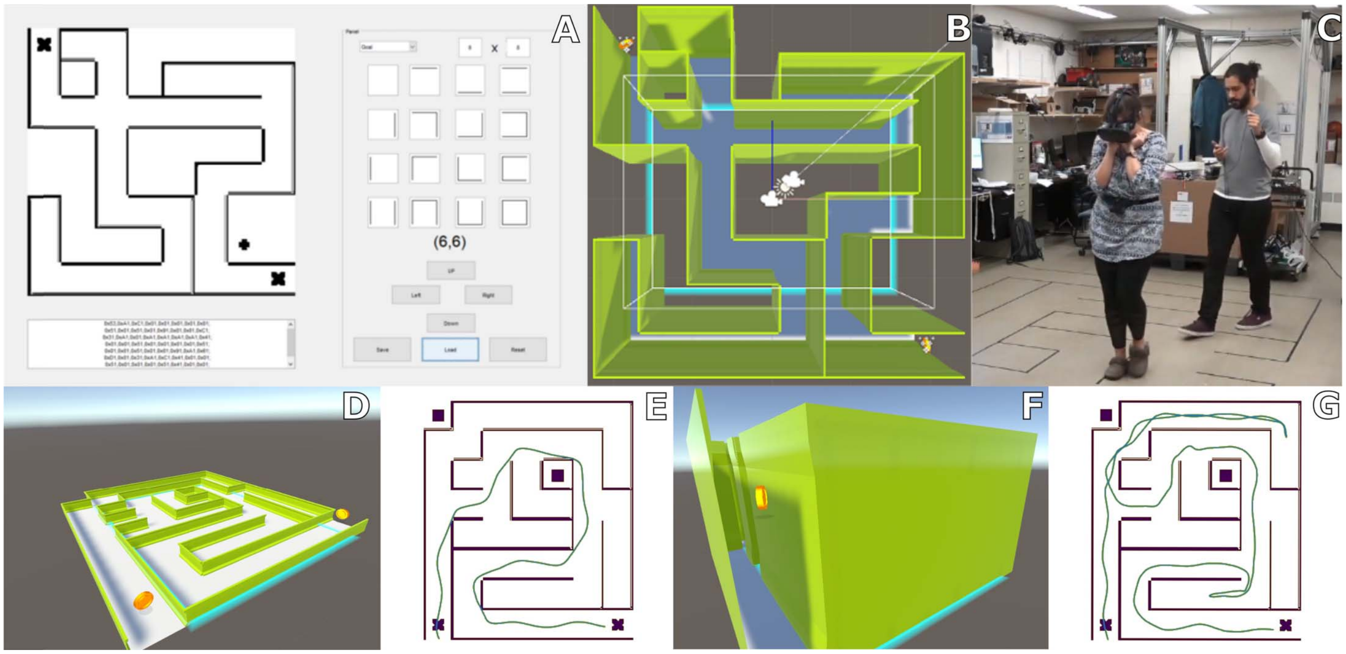

Fig. 1. Experimental Setup. (A) Matlab user Interface to build the plan of the maze. (B) Top view of the plan of the maze generated in Unity 3D. (C) Picture of a subject walking in the maze with the VIVE headset in the VE-W condition. (D, F) View of the virtual maze at entrance from the participant perspective in the VE-NW and the VE-W conditions. (E, G) Plan of the maze used in this experiment and path travelled by a representative subject in the VE-NW and VE-W conditions. Human subjects gave permission for the use of their identifiable images.

VE-NW - subjects were able to look at the entire floor plan, Figure 1D) and 2 m (with walls condition, VE-W – subjects could not see through the walls, Figure 1F). Participants experienced a first-person view of themselves walking in the virtual maze without full rendering of their body in the VE. Figure 1C shows a participant while walking in the maze with the virtual reality headset in the VE-W condition. Figure 1D-1G show the virtual maze at the entrance from a participant perspective, the plan of the maze and the path travelled by a representative subject in the VE-NW and VE-W conditions, respectively.

C. Experimental Protocol

Participants completed the FMT in three different conditions: real environment (RE), VE with no walls (VE-NW), and VE with walls (VE-W). In each condition, a research assistant positioned the participants at the entry point of the maze and instructed them to find the way to the exit. A fixed 10-second planning period was given to plan the route. In the VE-W condition, during the planning period, the walls were kept at 0.02 m and then switched to 2 m at the end of 10 seconds. The order of conditions (R: real, N: no-walls, W: walls) was counterbalanced between participants such that a total of 6 combinations were presented (RNW, RWN, NRW, NWR, WRN, and WNR). Using a stopwatch, a research assistant recorded the time elapsed from entry to successful exit from the maze. In addition, the length of the path and the numbers of stops and re-routes were recorded for 52 participants.

Among the many tests that measure executive function, the FMT has shown the best correspondence with the Trail Making Test (TMT) and the Digit Symbol Substitution Test (DSST) [12], [13]. In order to explore the association between navigational skill in the three environments and executive function, in between each condition, participants were asked to complete the TMT [24] and the DSST [25]. For the TMT, the time required to complete parts A (TMTA) and B (TMTB) were calculated. For the DSST, total number of correct answers given in 90 seconds (DSST-C), and time to complete all 110 blank spaces (DSST-T) were calculated.

D. Statistical Analysis

A three-way mixed design analysis of variance (rm-ANOVA) was performed to determine main and interaction effects of condition (within-subject factor, 3 levels: RE, VE-NW, VE-W), combination (between-subject factor, 6 levels: RNW, RWN, NRW, NWR, WRN, and WNR), and experience (between-subject factor, 2 levels: VR experience and no VR experience) with age as covariate. Time to complete the maze was used as dependent variable. If significant, main and interaction effects were followed up by pairwise comparisons with Sidak correction.

A Poisson regression analysis was performed to determine the effects of condition (3 levels: RE, VE-NW, VE-W) on the number of re-routings. The Wilcoxon signed-rank test was used to compare the length of the path in the VE-NW and the VE-W conditions. The relationships between the cognitive tests results (TMTA, TMTB, DSST-C, and DSST-T) and the time to exit the maze in each condition (RE, VE-NW, VE-W) were analyzed by a Spearman rank correlation. Moreover, the median value of the time to complete the maze in each of the three conditions (RE, VE-NW, VE-W) was calculated to subdivide the subjects in two groups: low navigational time

(LNT; below the median) and high navigational time (HNT; above the median). The performance of these two groups at the cognitive tests (TMTA, TMTB, DSST-C, and DSST-T) was compared with a Student's t test for independent samples [26] if both data sets were normally distributed or with the Mann-Whitney U test otherwise. The version of the t-test for unequal variance was used if data was not homoscedastic.

In order to analyze possible carryover effects at between-subjects level, three 1-way independent ANOVAs were performed to analyze the effect of time of display (1st, 2nd, or 3rd displays) using the time to exit the maze in each condition (RE, VE-NW, and VE-W) as dependent variables.

Statistical significance was set at $p<0.05$. The Lilliefors test, the Levene's test for equality of error variances, and the Mauchly's tests were performed to check the normality, homoscedasticity, and sphericity assumptions of data. For the ANOVAs, time was transformed with a natural logarithmic function because in none of the conditions we could assume that data was normally distributed ($p<0.019$). The Greenhouse-Geisser correction was applied because data violated the sphericity assumption ($p<0.001$). For the analysis of the performance of the LNT and HNT groups in the cognitive tests, data was normally distributed only when comparing the DSST-C formed with the median time to exit the maze in the RE and VE-W conditions. After natural logarithmic transformation, data was still not normally distributed for all conditions except for DSST-T and TMTB obtained by the groups formed with the median time to exit the maze in the VE-W and in the RE condition. So, data was analyzed with a Mann-Whitney U test.

The material generated during the current study is available from the corresponding author with a reasonable request.

III. Results

All participants completed the experiment without adverse events and none reported cybersickness. Table I reports the characteristics of the participants, their performance in the cognitive tests, and the frequency of appearance of each combination of the mazes.

Fig. 2 reports the time to complete the FMT for each of the three conditions. Time ($p<0.001$) was significantly affected by the condition factor. Post-hoc analysis revealed a significant difference between all the three conditions ($p<0.001$). Time to exit in the VE was greater than in the RE, irrespective of wall height ($p<0.001$), and time to exit in the VE-W was greater than in the VE-NW ($p<0.001$). No significant main effects of combination ($p=0.381$), or experience ($p=0.468$) were found. As expected, a significant main effect of age covariate was found ($p<0.001$). The interaction effects between condition and the other factors showed a trend but were not statistically significant (condition × experience: $p=0.101$; condition × combination: $p=0.063$; condition × age: $p=0.109$). Differences between the VE-NW and VE-W conditions tended to be smaller if participants had previous experience with walking in VR and if the VE-W was presented as the last condition.

Number of re-routes were significantly affected by the condition ($p<0.001$). They were significantly higher in the VE-W than the other two conditions ($p<0.001$). Indeed, none of the participants made re-routes in the RE condition; only one participant made a re-route in the VE-NW condition; and 35 participants made at least one re-route in the VE-W condition (range: 0-5 re-routes). The length of the path was significantly higher ($p<0.001$) in the VE-W (14.8 ± 6.1 m) than in the VE-NW (9.8 ± 0.8 m) condition.

Table II reports the results of the correlation analysis. As expected, time to complete the FMT in the three conditions (i.e., RE, VE-NW, and VE-W) were positively correlated ($r \geq 0.323$, $p \leq 0.016$). Time to complete the FMT in the

TABLE I
Characteristics of Study Population (N=55)

Age [yrs.]	32.7 ±16.6
Gender [female/male]	16/39
Height [cm]	173.6±8.8
Body mass [kg]	74.2±18.0
VR Experience [yes/no]	15/40
TMTA [s]	26.4±13.6
TMTB [s]	59.2±23.7
DSST-C [#]	66.9±12.8
DSST-T [s]	125.2±27.3
RNW [#]	10
RWN [#]	9
NRW [#]	9
NWR [#]	9
WRN [#]	10
WNR [#]	8

Values are reported as mean ± one standard deviation.
TMTA, TMTB: Trail Making Tests Part A and B. DSST-C, DSST-T: Digit Symbol Substitution Test: Number of correct answers in 90 second and time to complete 110 answers.

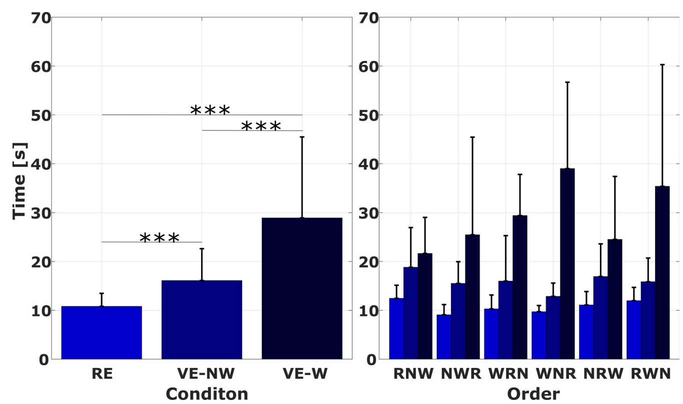

Fig. 2. Time to complete the Floor Maze Test (FMT) in the Real Environment (RE), Virtual Environment with no walls (VE-NW) and Virtual Environment with walls (VE-W). The order of conditions was counterbalanced between participants for a total of six combinations (RNW, RWN, NRW, NWR, WRN, and WNR). Left and right graphs represent the effect of condition and combination, respectively. * symbols indicate a significant difference between conditions as result of the pair-wise comparisons with Tukey-Kramer correction (*$p < .050$, **$p < .010$, ***$p < .010$). Values are reported as mean±one standard deviation.

TABLE II
SPEARMAN CORRELATION COEFFICIENTS OF SPATIAL & COGNITIVE TESTS

	RE	*VE-NW*	*VE-W*	*TMTA*	*TMTB*	*DSST-C*	*DSST-T*
RE	*1*						
VE-NW	***0.639*** ***	*1*					
VE-W	***0.323*** *	***0.443*** ***	*1*				
TMTA	*0.101*	*0.166*	***0.310*** *	*1*			
TMTB	*0.057*	***0.316*** *	***0.336*** *	***0.629*** ***	*1*		
DSST-C	*0.001*	*-0.208*	***-0.295*** *	***-0.556*** ***	***0.585*** ***	*1*	
DSST-T	*-0.017*	*0.209*	***0.298*** *	***0.528*** ***	***0.355*** ***	***-0.989*** ***	*1*

When the p-value is statistically significant, it is highlighted in bold. (*p < 0.05, **p < 0.01, ***p < 0.001). Spatial Tests: RE, VE-NW, VE-W: Time to complete the Floor Maze Test in the real environment, in the virtual environment with no walls and in the virtual environment with walls. TMTA, TMTB: Time to complete the Trail Making Test Part A and B. DSST-C, DSST-T: Number of correct answer given in 90 s and time to complete 110 blank spaces in the Digit Symbol Substitution Test (DSST).

VE-W condition was correlated with results of all the cognitive tests (i.e., TMTA, TMTB, DSST-C, and DSST-T, $|r| \geq 0.295$, $p \leq 0.029$). Time to complete the FMT in the VE-NW condition was positively correlated only with time to complete the TMTB test ($r = 0.316$, $p = 0.019$). Time to complete the FMT in the RE condition was not correlated with any of the cognitive tests.

A median time to exit from the maze of 10.28 sec, 14.31 sec, and 24.8 sec, divided participants with low navigational time (LNT; below the median) and high navigational time (HNT; above the median) in the RE, VE-NW, and VE-W conditions, respectively. Table III reports the group comparison of the cognitive performance in each test (DSST-C, DSST-T, TMTA, and TMTB) for each condition (RE, VE-NW, and VE-W).

Participants with LNT in the VE-W condition were significantly better in the TMTA, TMTB, DSST-C, and DSST-T ($p \leq 0.039$). Participants with LNT in the VE-NW condition were significantly better in the TMTB ($p=0.034$).

Table IV shows the results of the independent ANOVA. Across different participants, time to exit the maze differed between 1st, 2nd, and 3rd displays only in the RE condition ($p=0.003$). Post-hoc analysis revealed that time to exit the maze was significantly lower during the 3rd display with respect to the 1st one ($p<0.001$). Also in the VE-W condiiton, time to exit the maze tended to be lower during the 3rd display even if the ANOVA was not statistically significant.

IV. DISCUSSION

This study aimed to: (i) investigate the differences in performance between similar real and virtual versions of the Floor Maze Test (FMT); (ii) analyze the contribution of distal visual cues by adding walls in the virtual version of the FMT; and (iii) explore associations between navigational skills in the three environments and cognitive measures of executive function.

As hypothesized, time to complete the maze in the virtual environment was significantly higher than in the real environment, irrespective of wall height. This discrepancy could be due to a lower ability of subjects to correctly plan the exit of the maze in the planning phase and/or difference in gait characteristic in real and virtual environments.

In the VE-NW condition, despite the higher time, only one participant re-routed the path while exiting it, reflecting no differences with the RE in the acquisition of spatial information for planning the exit of the maze. Similarly, real and virtual reality versions of the Walking Corsi Test have been proved to be equivalent in measuring topographical memory and planning when active movement is not involved [19]. Accordingly, the higher navigational time encountered in the VE-NW condition is presumably due to differences in gait characteristic and not due to an increased navigational difficulty [22], [27], [28]. Walking over-ground in a VR headset causes an initial reduction of stride length, increase in step width and longer stride times [27], [28]. This may be due to the smaller field of view, the misinterpretation of the distance due to incorrect depth cues provided to the human eye and the lack of visual information about self-motion when looking through the VR headset [27]. The effect is transitory and participants are able to adapt their gait over time to reduce these initial differences [22]. In this experiment, we did not give participants any time to adapt to the virtual environment. Navigating in the VE-NW condition is likely to be associated with experience in handling walking with room-scale VR setups. Accordingly, we cannot exclude that, if we would have given participants more time to familiarize themselves with the virtual environment, the performance in the RE and VE-NW condition would have been similar.

The introduction of walls in the virtual environment (VE-W) increased the time to complete the FMT, the number of reroutes and the length of the path. Even if we cannot exclude that the increase in difficulty of the task was caused also by a higher competition between sensorimotor and cognitive resources due to the higher amount of visual information experienced in the VE-W condition [15], we believe that this result mainly reflects the importance of distal visual clues for spatial navigation. Lack of visual clues makes the task more difficult because of the associated higher demand for spatial abilities [7]. While in the VE-NW, the FMT could be taken as a vista space (i.e., participants are able to see the entire maze from any point), the introduction of walls changed the FMT to an environmental space (i.e., participants need to move around to experience the whole space) [7]. Successful navigation in environmental space involves a number of processes that are not necessary when navigating in vista space [7]. In the VE-W condition, the entry and exit points cannot be reached by simple visual inspection. This condition presumably draws more on navigational abilities because participants are required to memorize the floor plan in the planning period and have to translate this into an egocentric reference frame in order to find the exit of the maze.

Most common navigation tasks use vista space paradigms [7]. With the VR-FMT, participants can navigate actively within virtual, but realistic, spaces that can be

TABLE III
PERFORMANCE AT THE COGNITIVE TESTS OF THE LOW NAVIGATIONAL TIME (LNT) AND HIGH NAVIGATIONAL TIME (HNT) GROUPS

	RE			*VE-NW*			*VE-W*		
	HNT	*LNT*	*P-VALUE*	*HNT*	*LNT*	*P-VALUE*	*HNT*	*LNT*	*P-VALUE*
TMTA [s]	*28.8±18.0*	*24.3±6.9*	*0.957 (MW)*	*28.5±17.5*	*24.6±7.9*	*0.809 (MW)*	*30.1±17.8*	*22.8±6.2*	***0.0395 (MW)***
TMTB [s]	*59.7±24.4*	*60.4±23.6*	*0.785 (LTT)*	*66.8±28.2*	*51.4±15.8*	***0.034 (MW)***	*66.6±27.8*	*51.8±16.9*	***0.0274 (MW)***
DSST-C [#]	*67.0±12.8*	*66.3±13.4*	*0.831 (TT)*	*64.7±12.6*	*69.0±13.0*	*0.431 (MW)*	*63.1±15.2*	*70.4±8.8*	***0.035 (TT)***
DSST-T [s]	*124.6±27.2*	*127.0±28.7*	*0.637 (MW)*	*129.7±30.0*	*121.1±24.7*	*0.436 (MW)*	*135.0±34.8*	*116.1±14.0*	***0.017 (LTT)***

Groups were defined based on the median time to exit the maze separately for the 3 conditions (RE: Real Environment. VE-NW: Virtual Environment with no walls. VE-W: Virtual Environment with walls). The type of test used for determining the p-value is indicated in superscript: TT: independent samples t-test; LTT: independent samples t-test after logarithmic transformation; MW: Mann-Whitney U test. DSST-C: total number of correct answers given in 90 seconds. DSST-T: time to complete all 110 blank spaces. TMTA: amount of time required to complete part A. TMTB: amount of time required to complete part B. When the p-value is statistically significant, it is highlighted in bold. Values are reported as mean±one standard deviation.

TABLE IV
INDEPENDENT ANOVA FOR TESTING THE EFFECT OF TIME OF DISPLAY

	1ST DISPLAY	*2ND DISPLAY*	*3RD DISPLAY*	*P-VALUE*
RE [s]	*12.2±2.6*	*10.7±2.7*	*9.4±1.7*	***0.003***
VE-NW [s]	*16.2±5.5*	*16.2±6.9*	*15.9±7.3*	*0.911*
VE-W [s]	*33.7.3±13.8*	*30.4±22.5*	*23.0±10.1*	*0.074*

When the p-value is statistically significant, it is highlighted in bold. RE, VE-NW, VE-W: Time to complete the Floor Maze Test in the real environment, in the virtual environment with no walls and in the virtual environment with walls.

modified. The possibility to manipulate environmental features based on particular needs (e.g., switch from vista to environmental) is an advantage with respect to classical active tests for spatial navigation because this allows for an in-depth study of different aspects of navigational abilities and opens up new rehabilitative perspectives.

Time to exit the maze in the VE-W condition was the only outcome that correlated with the results of all cognitive tests. Moreover, results demonstrated that only in the VE-W condition (when distal clues were removed), participants with lower navigational time showed better performances in the cognitive tests than individuals with higher navigational time. Taken together, the results of this study suggest that the VE-W condition could potentially better identify early cognitive and navigational deficits.

The original version of the FMT has been shown to correlate with measures of executive cognitive functions, such as the DSST-C and the TMTB, in older adults, people with mild cognitive impairments and Alzheimer Disease [9], [12], [13]. However, no results have been provided for a general population of healthy adults as the one used in this study. It can be assumed that navigating in the real environment does not challenge enough the cognitive ability for this population as it is a simple task and does not place a higher demand on the executive function [23]. In addition, the plan of the maze used in this study was simpler than previous ones [12].

The present study can have positive implications for early detection and treatment of spatial navigation disorders. Although paper and pencil tests, computer games and VR environments have been used to study navigation, they do not necessarily correlate with real spatial tests [29]. This may be because they involve in-place (non-active) navigation through the environment that may recruit different brain regions than real (active) navigation [30]. On one hand, in-place navigation has the advantage that a small space is needed to administer the task and there is no bias in time recordings due to differences in participants' physical features such as height, walking speed, and age [19]. On the other hand, when navigating in place, vestibular and proprioceptive information about linear and angular movements are unavailable and the only information about self-motions is given through external inputs, such as visual and auditory cues [19]. Real navigation in the environment allows to include both internal body information generated by self-movement and external inputs from the outside world [31]. Moreover, there is increasing evidence that cognitive performance is strongly associated with characteristics of gait and balance [32], [33] and gait deficits occur early in the elderly, preceding declines in cognitive tests [34]. Hence, incorporating active gait into spatial navigation assessments not only provides more ecological validity by simulating real-space navigation but allows to identify modifications of gait that may be associated with cognitive decline.

To the best of authors' knowledge, this is the first study that systematically uses a fully-immersive VR headset to develop an active navigation test for real-space applications. Many VR tools aimed at specifically measuring navigational skills use only simulated navigation by means of a keyboard that moves the participants view or avatar in VR environments projected in 2-dimensions, or on head-mounted screens [17]–[21]. Studies have been conducted with participants performing an overground navigational task in VR and have considered: (i) how walking overground with a VR headset resembles walking in the real environment (RE) [22], [27], [28] and how humans react and adapt to visual perturbations [22], [35]; (ii) immersion capabilities and objective parameters of the tracking system [36]; (iii) the effects of VR in distance perception and spatial judgments [37]; (iv) ways in which visual cues and bodily cues from self-motion are combined in spatial navigation [31]; and (v) the effect of body-based sensory information on route knowledge [38]. Even if the participants were actively walking in the virtual environment, these studies were mainly aimed to analyze motion and perception, not navigational skills and their correlations with cognitive executive function.

The present study has several limitations. The same maze was used in the three conditions at within-subject level and we cannot exclude the existence of carryover effects. However, adopting this experimental design while counterbalancing the possible combinations allowed increasing statistical power and minimizing random noise. The effects of carryover effects were analyzed at between-subject level and results suggested that only for the RE and VE-W condition, the time to exit the maze decreased during the 3rd display with respect to the 1st display. We can infer that repeating the same maze facilitated the task during the last display because participants were more comfortable walking in it and were able to memorize the plan of the maze. Future experiments should investigate carryover effects at intra-subject level by asking participants to complete the VR-FMT multiple times in the same condition (e.g., VE-W). Due to space and technological limitations, we were unable to reproduce the same plan used in Sanders et al. [12]. The current version of the HTC headset was able to track a limited area of 4 m $\times$ 4 m, that restricted the dimension of the maze. Future experiments could be performed in larger areas thanks to the larger tracking field of new versions of the device (10 m $\times$ 10 m). The protocol lacked tests for memory and spatial ability that could have potentially added useful insight. Future experiments will include additional tests to study associations between maze complexity, memory and navigational abilities.

The performance of the VR-FMT likely depends on both cognitive and motor abilities if considering only the time to exit. Some applications may require the measures of pure cognitive deficits. In order to better disentangle the influence of cognitive and gait deficits, the number of re-routes or the length of the path should be used instead. Indeed, by measuring the optimal path to exit, the influence of motor deficits is attenuated. However, future experiments should include a comparison between passive and active versions of the VR-FMT to clarify what is the effect of active navigation on the performance.

The experiment was performed by healthy subjects and the results are not generalizable for other population groups. However, the analysis of the behavior of healthy participants is the first and necessary step to identify an approach to base further studies on other population groups targeted for screening and training. Challenges when using this approach with older age groups with cognitive deficits include the lack of experience with VR, the increased susceptibility to cybersickness, and the age-related difficulties in balance and gait that may require older adults to prioritize sensorimotor processing over cognitive processing in order to reduce the risk of falling in multiple-task situations [15]. Some of these problems might be alleviated in future generations as they become more used to the integration of VR in their everyday life. However, some expedients may be taken, such as providing sufficient familiarization in VR before testing, providing support in the form of walking aids, and simplifying as much as possible the experimental setup [15].

Given the cohort of healthy adults, resolving the FMT could have been easy for some participants, thus limiting how much knowledge we can draw from this experiment. This is true for the RE and VE-NW conditions but not in the VE-W condition. Without distal visual clues, majority of the participants made re-routings of their path while completing the FMT. This indicates that a certain level of challenge was presented. Even if this set-up is intended to be used in clinic with older population where the tasks in the RE and VE-NW conditions may not be as easy as for a healthy cohort, the results of this study indicates that the VE-W condition poses a greater challenge to the spatial abilities of participants and may better distinguish gait and cognitive deficits.

V. Conclusions

We successfully developed a fully-immersive virtual version of the floor maze test. Mazes with preferred complexity and dimension with walls of desired height and the width can be built and loaded with an easy computer interface in order to challenge navigational ability and mask visual clues.

Time to complete the maze in the virtual environment was higher than in the real environment, irrespective of wall height. The introduction of walls in the virtual environment increased the time to complete the test. Only the performance in this condition correlated with the results of all the cognitive tests and participants with low navigational time outperformed the participants with high navigational time in all the cognitive tests. The present study represents an initial investigation that may help the development of new VR methods for early detection and remediation of cognitive and navigational deficits.

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