Virtual navigation tested on a mobile app is predictive of real-world wayfinding navigation performance

Coutrot, A.[1,2], Schmidt, S.[1], Coutrot, L.[1,3], Pittman, J.[1], Hong, L.[1], Wiener, J. M.[4], Hölscher, C.[5], Dalton, R.C.[6], Hornberger, M.[7], Spiers, H. J.[1]

1 Institute of Behavioural Neuroscience, Department of Experimental Psychology, Division of Psychology and Language Sciences, University College London, London, United Kingdom.
2 Laboratoire des Sciences du Numérique de Nantes - CNRS - Université de Nantes, France.
3 Institut Jean Nicod, ENS, EHESS, CNRS, Paris, France.
4 Department of Psychology, Ageing and Dementia Research Centre, Bournemouth University, Poole, United Kingdom.
5 ETH Zürich, Swiss Federal Institute of Technology, Zürich, Switzerland.
6 Department of Architecture and Built Environment, Northumbria University, Newcastle upon Tyne, United Kingdom.
7 Norwich Medical School, University of East Anglia, Norwich, United Kingdom.

Abstract

Virtual reality environments presented on tablets and smartphones have potential to aid the early diagnosis of conditions such as Alzheimer's dementia by quantifying impairments in navigation performance. However, it is unclear whether performance on mobile devices can predict navigation errors in the real-world. We compared the performance of 60 participants (30 females, 18-35 years old) at wayfinding and path integration tasks designed in our mobile app 'Sea Hero Quest' with their performance at similar tasks in a real-world environment. We first performed this experiment in the streets of London (UK) and replicated it in Paris (France). In both cities, we found a significant correlation between virtual and real-world wayfinding performance and a male advantage in both environments, although smaller in the real world (Cohen's d in the game = 0.89, in the real world = 0.59). Results in London and Paris were highly similar, and controlling for familiarity with video games did not change the results. The strength of the correlation between real world and virtual environment increased with the difficulty of the virtual task, indicating that Sea Hero Quest does not merely capture video gaming skills. However, we did not find such correlation in our path integration task. The fact that Sea Hero Quest wayfinding task has real-world ecological validity constitutes a step toward controllable, sensitive, safe, low-cost, and easy to administer digital cognitive assessment.

Keywords: spatial cognition, virtual environment, real world environment, gender differences, dementia

1 Introduction

Spatial ability assessment provides the potential to act as an early stage diagnostic tool for Alzheimer's dementia (AD), because spatial disorientation is one of the earliest symptoms [13, 24, 26, 31]. Currently there is no standardized test for navigation deficits with AD patients, as diagnostics measures are still focused on episodic memory deficits, despite their low sensitivity and specificity for identifying at-risk individuals [6]. Virtual reality (VR) provides a powerful mean to study and quantify how humans navigate, because the properties of virtual environment can be completely controlled and repeated across participants. Since the late nineties, it has been a critical tool to understanding how brain regions support navigation and unveiling the structural and functional neural correlates of spatial navigation [9, 15, 20]. VR tests of spatial cognition have proved more sensitive in identifying spatial navigation deficits in patient populations compared to more classic visuospatial 'pencil-and-paper' tests like the Mental Rotation Test [17]. For older patients, VR has the added advantage a less costly and safer alternative to real-world navigation tests, which are time and space consuming, as well as difficult to administer to a population sometime less able to walk. Until recently most VR used in research was presented on a desktop display and movement controlled via a joystick or keyboard. Such an interface presents difficulties for people who are in the age range where AD may likely onset (50-70 years old) [11]. However, with the advent of tablet and smart-phone touch screen mobile devices, old participants have found engaging in VR tasks much easier [27]. We recently developed a VR navigation task for mobile and tablet devices – Sea Hero Quest [7] – with aim that this may provide an early diagnostic for AD. For this test to be useful it is important that it has real-world validity, with errors on the VR task predicting errors in real-world navigation experience.

Past research comparing navigation in real and VR environments has generally found a good concordance in performance across both environments in the normal population [4, 21, 23, 30, 34], in younger and older age groups [8], in individuals with brain injury [14, 25], in chronic stroke patients [2], and in patients with Mild Cognitive Impairment (MCI) or early AD [5, 8], for reviews see [3, 6]. However, this consistency seems to be modulated by the type of spatial navigation task: in [28], the authors show that performance in real life and virtual environments were similar for tasks such as landmark recognition or route distance estimate, but different for pointing to the beginning and endpoint of the route, or drawing a map of the route.

Numerous studies found a male advantage for navigation in VR tasks [1, 7, 10, 12, 18], but only a few looked for gender differences in real-world navigational tasks [16, 29]. This led some authors to suggest that previously reported gender differences in spatial ability may be driven by familiarity with technology, men being more comfortable with virtual tasks than women due to more exposure to video games [22].

Most prior studies comparing VR and real-world performance have used desktop VR or immersive VR to simulate environments, and paper and pencil tests such as line orientation, road map, or delayed recall when assessing ‘real world navigation behavior’. A few authors designed actual navigation tasks but often in a limited spatial range, like the lobby of a hospital [8]. A notable exception is [16], where the authors tested 978 military college students on a 6 km orienteering task and replicated many laboratory-based findings, including gender differences. However the authors did not test their participants in a VR task and thus couldn’t directly compare the two environments.

Here, for the first time we directly compare in a within-subject design the spatial navigation performance measured on mobile or tablet device with our Sea Hero Quest virtual tasks, and in a large-scale real-world environment covering a whole neighborhood of London (behind the British Museum) and of Paris (behind the Montparnasse cemetery). We designed the real-world counterparts of the Sea Hero Quest wayfinding and path integration tasks, which are known to tap into different cognitive processes [7]. We compared participants’ performance at each task in the virtual and real world environments while controlling for participants’ gender, familiarity with video games and for task difficulty.

2 Methods

The experiment was split into 2 main parts, see Figure 1. First, participants were tested on specific levels from Sea Hero Quest [7] on a tablet. Second, they were tested on equivalent tasks in the real world. Participants were also asked to answer a few demographic questions. We first ran this experiment in London in summer/fall 2017. We then replicated it with a different team in Paris in spring 2018. The whole experiment lasted around three hours.

2.1 Participants

In London - We tested 30 participants (15 males), aged 18-30 y.o. (M= 21.96, s.d.= 2.55). Data from one participant was missing due to a technical problem. Real world wayfinding data from six participants (three males and three females) were discarded due to GPS recording issues. Participants had normal or corrected to normal vision and gave their written consent to participate. Path integration data was not collected for the first 11 participants as this task was not yet implemented. Participants received 3 class credits or £20 for their participation.

In Paris - We tested 30 participants (15 males), aged 18-35 y.o. (M= 24.27, s.d.= 3.31). Real world wayfinding data from four participants (one male and three females) were discarded due to GPS recording issues. Participants had normal or corrected to normal vision and gave their written consent to participate. Participants received 30 euros for their participation.

2.2 Virtual tasks

We devised a mobile video game designed to measure human spatial navigation ability through gameplay - Sea Hero Quest (SHQ)[1]. This video game involves navigating a boat in a virtual environment (lake or river networks) and has been extensively described in [7]. It features two main tasks, which has been designed to tackle different aspects of spatial navigation.

1- Wayfinding. Participants were required to view a map displaying current position and future goal locations to find (Figure 1A-B). Participants could study the map without time restrictions and had to navigate to the goal locations in the order indicated, e.g. goal 1 must be found first, then goal 2, etc. Goals were buoys with flags marking the goal number. The task is complete when all goals have been located. If the participant takes more than a set time, an arrow indicates the direction along the Euclidean line to the goal to aid navigation. On basis of the data from the online version, we selected a subset of 5 of the total 75 levels in the game that varied in difficulty: instruction level 1, and wayfinding task levels 6, 11, 16, and 43 (see Supplemental Figure S4). The helping arrow appeared after 80 s in level 1, 70 s in level 6, 80 s in level 11, 80 s in level 16 and 200 s in level 43. Performance was quantified with the Euclidean distance travelled in each level (in pixels). The coordinates of participants' trajectories were sampled at F_s = 2 Hz. We summed the distance travelled over levels 6 to 43. We did not include level 1 because it did not require any spatial ability (the goal was visible from the starting point) and was only designed to assess participants' ability to learn to control the boat.

2- Path Integration. Participants were required to navigate along a river with bends until they find a flare and shoot it back toward their starting position. Participants could choose among three directions, as shown in Figure 1C. We selected a subset of 5 levels that varied in difficulty: level 14 had one bend, level 34 three, level 44 two, level 54 four and level 74 five, see Supplemental Figure 7A. Performance was measured with the number of stars obtained by the player. Stars were awarded based on participant's choice between 3 proposed directions: 3 stars for the correct answer (their starting point), 2 stars for the second closest direction, and 1 star for the third closest direction.

2.3 Real world task

1- Wayfinding. The real-world wayfinding task consisted of 6 wayfinding trials which varied in difficulty in terms of the number of streets to be navigated, the number of goals and the relative location of the goals to each other. Each trial was located in a different street network behind the British Museum in London and behind the Montparnasse cemetery in Paris. We chose less busy streets to avoid traffic and made sure the participants were not familiar with them. Before each trial, participants were shown a map that only indicated the facing direction, the network of the local streets and the location and the order of the goals (in London see Supplemental Figure 5, in Paris see Supplemental Figure 6). Maps were displayed on a tablet (Ipad MP24B/A, 9.7 inches). The goals were doors and gates with distinct features (e.g. specific colour, size, or material). Participants had up to 1 min to memorize the map (maximum length for Sea Hero Quest) before walking to locate the goals. During navigation they were provided with colour photographs of the goal. Based on pilot testing we set specific time limits for each route. We chose these time limits to allow for a few mistakes at a reasonable walking pace. Pilot testing indicated that if participants required any longer than that these

times they were likely guessing and had failed to remember the goal locations or street layout. If participants reached the limits of the defined region set by the experiment they were told by the experiment they had reached the edge of the search area and should turn back. In London, route one: 6 minutes, route two: 6 minutes, route three: 6:30 minutes, route four: 6:30 minutes, route five: 12 minutes, route six: 14 minutes. In Paris, route one: 5 minutes, route two: 8 minutes, route three: 8 minutes, route four: 9 minutes, route five: 16 minutes, route six: 20 minutes.
The coordinates of participants' trajectories were sampled at Fs = 1 Hz with the experimenter's smartphone GPS via the Beeline app. We visually inspected all recorded GPS trajectories to deal with potential losses of signal. For losses of signal where the participant did not make any turn, we linearly interpolated between the first and the last missing points. When we couldn't reconstruct the trajectory because the participant changed direction during the loss of signal, we couldn't reconstruct the trajectory and discarded the data (3.3% of the trials in Paris, 2.8% in London). Performance was quantified with the Euclidean distance travelled in each route (in meters). To take into account the fact that some participant did not finish some routes, we divided this distance by the number of goals reached by the participant plus 1. We added 1 to cope with cases where the participant didn't reach any goal (this only happened once). We called this metric normalized distance and summed it over routes 1 to 6.

2- Path Integration. The real-world path integration task consisted of 4 path integration trials which varied in difficulty in terms of the number turns they featured (1, 2, 3 and 4 turns, see Supplemental Figure 7B). To avoid familiarity effect, path integration routes were chosen not to intersect with any wayfinding route. Participants were required to follow the experimenter to an endpoint where they were asked to point back toward the starting point. We used a numeric compass to precisely record the direction.
Performance was defined as the inverse of the angle between the direction pointed toward by the participant and the ground-truth, in degrees. We then summed the absolute values of the path integration error angles.

3 Results

Table 1 quantifies the difficulty of each route in the real world task as the percentage of goals reached by the participants before the time limit. This goes from 99% in London (100% in Paris) for route 1 down to 74% in London (84% in Paris) for route 6. Table 1 also quantifies the difficulty of each level in the video game task as the percentage of participants that managed to complete the level before the helping arrow appeared. 100% participants successfully completed the first training level while only 47% participants in London (40% in Paris) completed level 43. Interestingly, level 11 seemed harder than level 16, which might be due to level 11requiring participants to turn back to meet the goals in order, which was not the case in level 16 (see Figure S4).

Correlation between performance in real world and virtual environments
The relationship between the wayfinding performance in the real world and in the video game is shown Figure 2A (in London) and 2B (in Paris). One can notice a few outliers in the upper right corner of the scatter plots. Traditional Pearson's correlation measure is known to be highly sensitive to outliers, which can severely bias the estimation of the strength of the association among the bulk of the points [33]. To deal with this, we used skipped-correlation, which protects against outliers by taking into account the overall structure of the data [32]. Outliers are detected using a projection method, removed, and Pearson's correlation is computed using the remaining data. Hence, Pearson's skipped correlation is a direct reflection of Pearson's r. We used an implementation of this algorithm available in a free toolbox [19]. The detected outliers are tagged in Figure 2A-B with black edges, and discarded from further analysis. 95% Confidence Intervals (CI) were computed via bootstrap: pairs of observations were resampled with replacement and their correlation values obtained and sorted. Values between the 2.5 and 97.5 percentiles yielded the 95% CI. Skipped correlation were significant both in London ($r = 0.46$, 95% CI = [0.14, 0.68], $p = 0.01$) and in Paris ($r = 0.57$, 95% CI = [0.37, 0.76], $p = 0.001$).

To confirm that our virtual task captured participants' wayfinding ability, we checked whether the strength of the correlation between performance in real world and in the video game was modulated by the difficulty of the virtual task. Under this hypothesis, the correlation should be null between real world and level 1 performance, since level 1 is a training level where no spatial ability is required: the end goal is visible from the starting point. The correlation should then increase with the difficulty of the level. We broke down the global correlation score for each Sea Hero Quest level, comparing participants' performance in real life with the distance they travelled in each levels. To increase the sample size, we combined the data recorded in London and in Paris. To do so we first performed a zscore on the data of each level in each city. In the following we work with this cross-city normalized metric, called Normalized Distance. The skipped correlation coefficient between the Normalized Distance in the real world and in level 1 is close to 0, confirming that this instruction level does not measure spatial ability. We sorted the game levels by increasing difficulty based on the results of Table 1: level 1, 6, 16, 11 and 43. As shown in Figure 2C, the skipped correlation coefficient increases with level difficulty, from $r = 0.06$ in level 1 to $r = 0.44$ in level 43.

The skipped correlation between real world and video game path integration score in Paris was not significant, $r = -0.23$, 95% CI = [-0.51, 0.08], $p = 0.11$. However, the sign of the correlation is logical since higher scores mean better performance in the game (number of stars) but not in the real world task (error angle). In London, the first 11 participants were not tested on path integration as this task was not yet designed. The skipped correlation based on the other 19 participants is consistent with Paris data: $r = -0.40$, 95% CI = [-0.73, 0.07], $p = 0.05$. However, correlational analyses with small sample size can lead to strongly biased correlation estimates and this result should be considered with caution.

Gender differences

For the wayfinding task, we found that in both environments male participants had an advantage, although smaller in the real world (Figure 2D). In the real world, Cohen's $d = 0.59$, 95% CI = [0.02 1.15], $t(47) = -2.08$, $p = 0.04$; in the video game, Cohen's $d = 0.89$, 95% CI = [0.35 1.42], $t(56) = -3.43$, $p = 0.001$.

For the path integration task, we did not find a significant gender difference. However, the tendency was similar to the wayfinding results, male having a small advantage in both environments, smaller in the real world. In the real world, Cohen's $d = -0.10$, 95% CI = [-0.79 0.60], negative values correspond to a male advantage; in the video game, Cohen's $d = 0.29$, 95% CI = [-0.40 0.99], positive values correspond to a male advantage. The gender effect size is much smaller for path integration than for wayfinding and is not significative, as shown by the wide 95% CIs.

Selection bias

To check whether the 60 participants we recruited for this experiment were representative of the much larger dataset recorded with the mobile version of Sea Hero Quest [7], we plotted in Figure 3 the performance of the participants at this study (vertical red dotted lines) against the corresponding distribution of the performance of the French and British Sea Hero Quest players from the original dataset (N = 78,724). Figure 3 clearly shows that the performance of the participants recruited for this study closely follows the performance distribution of the original dataset.

Influence of familiarity with video games

On average, females played video games 2.99 ± 8.38 hours per week and males played 2.95 ± 4.21 hours per week. To control for the influence of familiarity with video games on real world and virtual spatial abilities, we computed a multiple linear regression to predict performance based on gender and on the time participants spent playing video game (VGT), in hours per week. With normalized distances recorded in the real world wayfinding task, gender was a significant predictor ($t(47) = -2.22, p = 0.03$), but not VGT ($t(47) = 0.31, p = 0.76$). Similarly, with normalized distances recorded in the virtual wayfinding task, gender was a significant predictor ($t(55) = -3.44$, $p = 0.001$), but not VGT ($t(55) = -0.99$, $p = 0.32$).

With normalized error angles recorded in the real world path integration task, gender was not a significant predictor ($t(55) = -0.65$, $p = 0.52$), nor was VGT ($t(55) = 1.09$, $p = 0.28$). Similarly, with normalized flare accuracy recorded in the virtual path integration task, gender was not a significant predictor ($t(55) = -0.17$, $p = 0.87$), nor was VGT ($t(55) = 0.09$, $p = 0.92$).

Correlation between wayfinding and path integration
The skipped correlation between path integration and wayfinding scores is not significant both in the real world (Paris data): r = -0.06, 95% CI = [-0.34 0.44], nor in the virtual environment: r = -0.18, 95% CI = [-0.49 0.15]. Higher scores mean better performance in the path integration task in the game (number of stars) lower score mean better performance in the path integration task in the real world task (error angle), and in the wayfinding tasks in both environments (distance).

4 Discussion and future work

We report evidence that navigation performance on a mobile app based VR navigation task (Sea Hero Quest) is significantly correlated with performance in a real-world city street wayfinding task. We directly compared participants performance at a subset of Sea Hero Quest wayfinding levels with their performance at an equivalent task in Covent Garden, London. We found a strong correlation between the distance participants travelled in the video game (in pixels) and in the real world street network (in meters, measured by a GPS device). We replicated this result with another set of participants in a similar experiment in the Montparnasse area, Paris. The high similarity of the results in the two cities is a strong indicator of the robustness of the results presented above.

We did not find a significant correlation between the performance at the real world and the Sea Hero Quest path integration task. At least two reasons could account for this null result. First, as mentioned in the introduction, the consistency between spatial navigation ability in the real world and in a virtual environment task depends on the type of navigational task [28]. In particular, the aforementioned study reported a poor concordance for a task involving pointing to the beginning and endpoint of the route, which is quite close to our path integration task. This hypothesis is consistent with the weak correlations we found between wayfinding and path integration performances, both in the real world and in the virtual environment: the two tasks involve different cognitive processes, which don't generalize similarly from one environment to the other. Second, this null result could be caused by the low sensitivity of our virtual path integration task. Indeed, while in the real world performance was a continuous variable defined as the inverse of the error angle, in Sea Hero Quest it could only take three values: one, two, or three stars. This ternary metric might not be sensitive enough to capture subtle differences in the moderate sample size used in this study (60 participants), unlike the original Sea Hero Quest study on mobile and tablet (2.5m participants) [7].

We found a significant male advantage at the wayfinding task in both real world and virtual environments, although weaker in the real world. This difference in effect size between the two environments couldn't be explained by males being more familiar with video games, as suggested in a previous study [22] for three reasons. First, our male and female participants reported playing video games the same average duration per week (2.95 vs 2.99 hours per week). Second, when using gender and time playing video games (VGT) as covariates in a linear model to predict wayfinding performance in the real world (resp. in the virtual environment), gender came out as a significant predictor, but not VGT. Third, we found a very weak correlation coefficient (skipped Pearson's r = 0.06) between the performance at the real world wayfinding task and at the first training Sea Hero Quest level, which did not require any spatial ability (the endpoint being visible from the start). The strength of the correlation increased with the difficulty of the video game level (up to r = 0.44 in level 43), indicating that Sea Hero Quest does not merely capture video gaming skills.

Our findings are consistent with a number of studies that have compared real-world and VR navigation [1, 2, 4, 8, 14, 21, 23, 25, 28, 34], and extend the findings to tablet device presentation and real world spatial task spanning complex street networks. This is a useful step since it increases the ability to remotely test people. This is particularly valuable when certain categories of the population have difficulties in mobility, like older people. Currently our results focused on young university students, and it will be useful to extend to a broader population including elderly participants. Given that patients with Alzheimer's Disease experience real-world wayfinding problems early in the disease onset [5, 13, 24, 26, 31], the fact that the Sea Hero Quest wayfinding task has real-world ecological validity holds future promise for controllable, sensitive, safe, low-cost, and easy to administer digital cognitive assessment.

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