Behavioural Brain Research 225 (2011) 117–125

Contents lists available at ScienceDirect

Behavioural Brain Research

journal homepage: www.elsevier.com/locate/bbr

Research report

Simple gaze analysis and special design of a virtual Morris water maze provides a new method for differentiating egocentric and allocentric navigational strategy choice

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ARTICLE INFO

Article history:
Received 22 March 2011
Received in revised form 7 June 2011
Accepted 3 July 2011
Available online 8 July 2011

Keywords:
Eye tracking
Virtual reality
Spatial navigation
Egocentric
Allocentric
Orientation

ABSTRACT

We present a novel method of combining eye tracking with specially designed virtual environments to provide objective evidence of navigational strategy selection. A simple, inexpensive video camera with an easily built infrared LED array is used to capture eye movements at 60 Hz. Simple algorithms analyze gaze position at the start of each virtual maze trial to identify stimuli used for navigational orientation. To validate the methodology, human participants were tested in two virtual environments which differed with respect to features usable for navigation and which forced participants to use one or another of two well-known navigational strategies. Because the environmental features for the two kinds of navigation were clustered in different regions of the environment (and the video display), a simple analysis of gaze-position during the first (i.e., orienting) second of each trial revealed which features were being attended to, and therefore, which navigational strategy was about to be employed on the upcoming trial.

1. Introduction

A key problem in the study of human navigational behavior is the difficulty researchers have in discerning the strategies that participants use to complete navigation tasks [1]. There appear to be a variety of types of cognitive processing that can be classified into one of two distinct strategies for navigation. The first of these relies on the acquisition of simple stimulus–response associations between environmental stimuli and body-based responses such as “go towards this object” or “turn right at the corner” [2]. The second is “cognitive mapping” [3], the process of forming an internal representation of the environment.

The two types of cognitive processing underlying spatial navigation have come to be classified as egocentric and allocentric [4]. Egocentric navigation consists of executing stimulus–response associations between individual landmarks (environmental features) and body-based responses until an interim or final goal is reached. Egocentric navigational strategies (sometimes called non-spatial [1], or simple [5]) do not require knowledge of the relations among environmental stimuli. In contrast, allocentric navigation (sometimes called spatial [1,6]) consists of moving in distances and directions according to vectors computed to lie between the navigator’s current position and the destination [7]. These computations are based on a cognitive map which incorporates the spatial relations among landmarks in the environment as well as their relationship to the target destination. The “gold standard” for testing allocentric navigation is the Morris water maze (MWM) [8]. This task requires rats to swim to an invisible platform placed just below the surface in a round pool of milky water. The rat completes a number of trials from different start positions around the wall of the pool, and thus has to learn the location of the platform using available cues that include the arena wall (which is a uniform texture and color) and distal room cues located outside of the pool. The ability of the rat to directly return to the platform regardless of start position is taken to mean that the rat has formed a representation (or cognitive map) of the environment [8] and is using an allocentric system to navigate.

Recently, researchers have become interested in strategy use and selection in different paradigms. In general, researchers have differentiated navigational strategies through participant self-report or by combining self-report with inferences from behavioral data [1,9,10]. However, self-report is inherently subjective and it

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doi:10.1016/j.bbr.2011.07.005

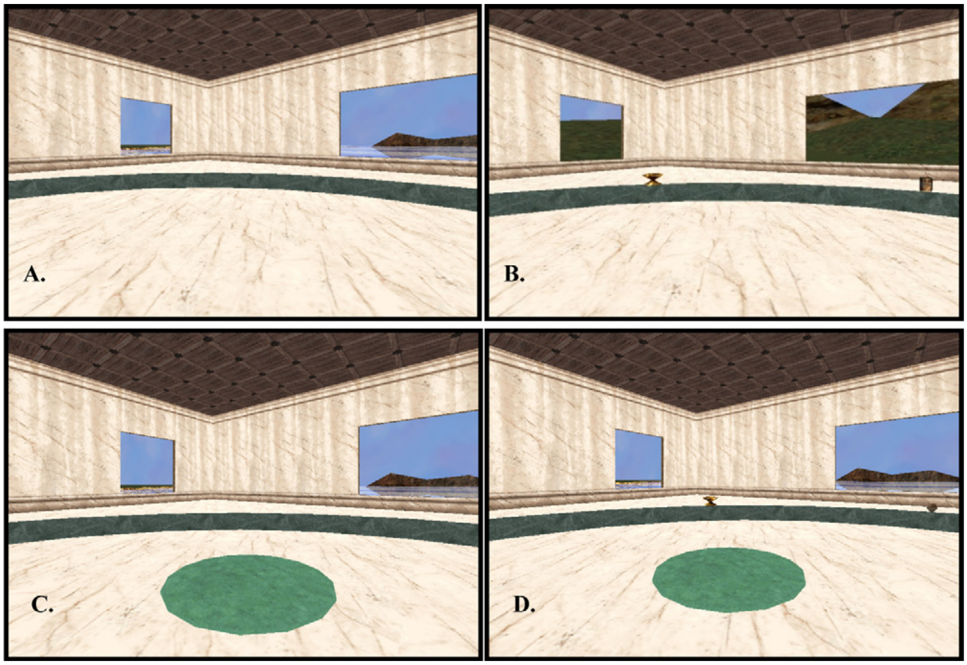

Fig. 1. Virtual environments. (A) Place maze, a virtual Morris water maze. (B) The Cue maze, a virtual landmark maze. (C) The Place maze with the platform visible in its fixed location (i.e., after the participant has stepped on it). Note that during trials, the platform's location can be identified only by a constellation of distal landmarks, forcing the participant to find it allocentrically. (D) The Cue maze with the platform visible (coincidentally) in the southeast quadrant, marked by the golden urn. Because the platform (and urn) change quadrants each trial, this proximal object provides the only means of identifying the platform location, forcing the participant to find it egocentrically.

would be beneficial to be able to identify navigational strategies in a more objective manner. Further, three studies (one animal and two human) have provided evidence that the selection of a navigational strategy (egocentric or allocentric) can be spontaneous and that the initial strategy can be switched mid-task in favor of another [1,6,9]. This is problematic for studies that assess navigational strategies only at the conclusion of testing, because animal subjects or human participants may be using more than one strategy at different times during the testing and because different strategies may lead to similar performance (see for example [11]). This use of spontaneous and variable strategy selection in response to environmental stimuli implies that in at least some navigational situations, the response to stimuli depends upon the state of the navigator. Clearly, it would be valuable to have an objective means of identifying selected strategies within a given session or even on a trial-by-trial basis.

The primary goal of the present study is to investigate the use of eye tracking as an objective, reliable method to discriminate egocentric and allocentric strategies within sessions and individuals.

The tracking of eye movements is a well-established method of analysis in psychological research. In early studies, eye movement tracking was used to record visual attention in studies of reading comprehension and selective visual attention (see for example, [12]). The increased availability of high quality eye tracking equipment has now made it possible to extend this research into even more applied fields (e.g., [13–15]). Eye-tracking has also been applied to studies of spatial cognition, but to date, most have presented stimuli that consist of static images on a computer screen [16–18]. Such studies fail to take into account that navigation can cause perceived stimuli to change: they appear, disappear, or change their relation to each other as the navigator moves. In a notable exception, eye movements in a complex, moving environment were recorded but these were used only to confirm post-session verbal reports [19]. Thus, there is a need to investigate navigational strategies using eye tracking while the participant is moving through space. Virtual environments are well suited to this task, but there are challenges to overcome.

The main difficulty with tracking eye movements in response to a dynamic, virtual environment is the sheer volume of data generated because the relation between gaze position and environmental features must be computed for each frame, and there can be up to 30 frames/s. In the past, such data analysis has been extremely labor intensive, leading to secondary problems with selection of data for analysis. For example, El-Nasr and Yan [20] investigated visual attention while participants played a complex three-dimensional video game. Analysis was accomplished manually using frame-by-frame extraction of coordinates. Due to this lengthy process, only six participants could be tested so generalization becomes problematic, and group studies using this method would be difficult. One approach used in the study of newspaper-reading overcomes this problem by organizing the computer presentation screens into discrete segments containing specific types of information (binning) [21]. This approach has the advantage of limiting the volume of data by measuring a percentage of gaze dwell time in a select area. So although the image presented on the screen is moving dynamically, researchers can still calculate the length of time participants spend looking at particular regions of the screen. This compliments studies of navigational strategy selection since areas of interest can be linked to allocentric and egocentric stimuli in a virtual environment. Recently we demonstrated that analysis of eye movements during orientation at the start of trials in an allocentric virtual MWM can be used to identify, trial-by-trial, participants' tendency to orient themselves to their location in space using an allocentric strategy [22].

This present article presents a method of discriminating between egocentric and allocentric navigation strategies on a trial-by-trial basis using eye tracking in a specially designed virtual MWM. There are two critical design features of the virtual maze used here. The first consists of a vertical separation of allocentric stimuli from other stimuli within the environment. That is, all distal features that can be used by the participant to establish their position in the maze are located above a horizon, and remain above that horizon regardless of where the participant is in the maze. The second important design feature was the adaptation of our standard allocentric maze to create a maze biased towards the use of egocentric strategies, by placing objects below this horizon and proximal to the goal location. In our standard maze, herein called the "Place maze", participants had to find and return to an invisible target platform in a fixed location in the absence of proximal stimuli (see Fig. 1). Therefore, participants had to use a constellation of distal landmarks (i.e., an allocentric strategy) to efficiently navigate to the hidden platform location. In the new adaptation of this maze, herein called the "Cue maze", the environment was identical, except for the addition of multiple objects in the environment, only one of which could be associated with a target platform, which now varied in location from trial to trial.

These two design features allowed us to analyze gaze positions to identify which strategy participants were using to orient themselves to the target location at the start of each trial. Because the Place maze is solved most efficiently using an allocentric strategy, and the Cue maze is solved most efficiently using an egocentric strategy, these two strategies should dominate in each of these two mazes. If there is a difference in the gaze positions which dominate in these two mazes, i.e., towards the distal features in the Place maze and the proximal features in the Cue maze, then this would provide strong evidence that this method of analyzing eye movements provides a good indication of whether an egocentric or an allocentric strategy is being used. We also analyzed the horizontal distribution of gaze in the Place and Cue mazes.

2. Method

2.1. Participants

Twenty-seven undergraduates (14 males and 13 females, mean age of 20 years) were recruited from the introductory psychology class at the University of Victoria. The data from four participants were not included because their eye movements could not be tracked reliably. In addition, there were errors in the data for two participants. Therefore, the analysis included data from 21 participants (11 males and 10 females). Participants all had normal or corrected-to-normal vision, and received credit towards their final grade in a Psychology course as compensation. The study was approved by the Human Research Ethics Committee at the University of Victoria.

2.2. Apparatus

We used two virtual MWMs, the Place maze and the Cue maze, built using the editor supplied by Unreal®; Epic Megagames (maze designs and software are available for collaboration). Both mazes were presented on a desktop computer with a 19 in. LCD monitor set to a resolution of 800 × 600. Participants experienced the virtual environments from a first-person view, and navigated with a joystick that allowed them to turn and move forward, but did not allow them to move in reverse. Backwards movement was prevented to simulate the swimming movements of rats within the MWM.

2.2.1. Place maze

The Place maze was designed to elicit allocentric navigation (see Fig. 1 and for a more detailed description see [23]). The Place maze environment consisted of a square arena room (75 m × 75 m) with windows through which an outdoor landscape could be seen. The arena room walls were featureless, except for windows, and were arbitrarily designated as north, south, east, and west. Within the room was a circular arena, 40 m in diameter, bound by a 1 m high wall that restricted the participants' movements to within the arena during trials without blocking their view of the windows and outdoor landscape. The landscape had a clear cardinality observable through every window: there were mountains to the north, water and an island to the south, with hills sloping from the mountains to the water. The sills of the windows and wainscoting formed a horizon that bisected the display into equal-sized upper and lower regions. Consequently all distal landscape features were located above the horizon and remained so regardless of the participants' position within the arena.

The navigational goal on every trial was a 6.7 m diameter platform, located in the center of the southeast quadrant. It was invisible until stepped on by the participant, at which point it rose to become visible, making an alerting sound. Trials always began inside the arena at one of the four cardinal points (north, east, south, west), with the participant facing towards the center of the room. Starting position varied in pseudo-random order, with all cardinal points being used in each set of four trials. Thus, at the start of each trial, participants were required to orient themselves to landscape features in the upper portion of the screen in order to identify their current location, and therefore, the position of the platform relative to their current location. In sum, the Place maze promoted the use of an allocentric navigational strategy through a combination of the fixed platform location, varying start positions, lack of proximal stimuli and the configuration of distal stimuli that were always located above the horizon, in the upper position of the display.

2.2.2. Cue maze

The Cue maze was designed to elicit egocentric navigation. The maze was identical to the Place maze in all respects except for the addition of eight objects (boxes, barrels, etc.) perched in fixed locations on the arena wall, equidistant from each other and at cardinal points (see Fig. 1). The location of the platform changed on each trial, but a single object (a golden urn) was substituted for the usual object nearest its position so that it always indicated the correct platform location. Start positions were varied from trial to trial so that at the start of each trial, participants had to orient themselves. Because the platform varied in position relative to the room cues, the golden urn was the only stimulus in the room that accurately predicted the goal location. The size of the objects was manipulated so that they were just small enough to always be located below the horizon (the window sill). Thus in the Cue maze the only way for participants to orient themselves to the platform location was to attend to features below the horizon.

2.2.3. Eye tracking

The eye-tracking system used in these studies was developed by CanAssist (Canadian Institute for Accessibility and Inclusion) at the University of Victoria. The equipment consisted of a digital camera (Flea Firewire, Point Grey Research, Vancouver, BC) fitted with an LED-infrared lighting system (Hamamatsu Corp.) consisting of a frame of lights placed around the lens. The camera/LED assembly was mounted on a swivel. The infrared light from the camera was reflected from the cornea of one of the participant's eyes and into the digital camera lens. A dedicated desktop computer recorded the eye movements of participants as positional 'x–y' coordinates at a frequency of 60 Hz and, on a second monitor visible only to the experimenter, displayed the current gaze position as a red ball, overlaid onto the maze trials. In this way, the experimenters were able to view the eye movements of the participants as they navigated the mazes. Participants were informed that their eye movements were being tracked. The eye tracking data was analyzed using MATLAB® (The Mathworks Inc.) to assess the location of gaze during the first second of the relevant trials. More detailed eye tracking apparatus specifications and the data collection and analysis software are available at (http://web.uvic.ca/psyc/skelton/EyeTracker.htm).

2.3. Procedures

2.3.1. Eye tracking set-up

The participants' dominant eye was identified by having them look through a small kaleidoscope. Participants were then seated in an adjustable chair with their chin on a chin rest. Both the chair and chin rest were adjusted for comfort. The camera was directed towards the participant and further adjustments were made to center the image of the dominant eye on the computer monitor. Once the participant was positioned correctly, eye movements were calibrated to the computer screen using a 9-point calibration in which a 3 × 3 grid of small circles spanned the height and width of the display. In order to elicit continuous foveation, each small circle displayed a series of letters and the participant was asked to continue looking at the circle while repeating the letters silently. During this phase participants were asked not to blink if possible. From this point onwards, the tracker's estimate of the gaze position was indicated on the second computer monitor, out of sight of the participant. The position of the horizon was then identified by displaying an image of a wall and window and having the participant watch the tip of a pen moved horizontally along the horizon (the window sill and wainscoting) at the vertical center of the display.

2.3.2. Maze trials

2.3.2.1. Exploration/practice trial. Table 1 gives the types of maze trials, their number and purpose. The start position of the first exploration trial in both the Place and Cue mazes was outside the arena by the south window, facing into the room. All participants were told that they could explore the room for as long as they liked and they were encouraged to visually explore the interior and exterior of the room (through the windows). The exploration trial ended when the participant indicated comfort with the joystick and satisfaction with their exploration of the virtual environment.

2.3.2.2. Visible platform trials. During the four "visible platform" trials a large, green, circular platform was visible on the floor of the arena in the center of a different quadrant for each trial. Each trial position was different, with all start positions at a cardinal point just inside the arena wall. Participants were instructed to walk to the platform as quickly and directly as possible. Once there, they were instructed to stay on the platform and encouraged to look around the room.

2.3.2.3. Place maze trials. Testing in the Place maze consisted of 12 trials. The first was a free exploration trial that began at one of the cardinal points just inside the arena wall. Participants were allowed to explore the inside of the arena for as long as they liked. The next ten trials started at one of the four cardinal points just inside the arena, facing the opposite wall. Start positions varied in a fixed, pseudorandom order. The platform was in a fixed location in the center of the southeast quadrant and was invisible until stepped on. Participants were informed that the platform

Table 1
Summary of virtual maze tasks and the purpose of each.

Task	Purpose
Room exploration trial	To allow participants to familiarize themselves with the virtual environment and practice moving around with the joystick
Visible platform trials (4)	To guarantee participants have mastered the non-spatial requirements of the task
Place maze exploration trial	To introduce participant to the virtual room they will be tested in
Place maze invisible platform trials (10)	To test the participants ability to navigate to a fixed invisible platform using distal landmarks.
Cue maze invisible platform trials (10)	To test the participants ability to navigate to a cued invisible platform using proximal landmarks
Probe Trial	To test how well the participant had learned the platform location

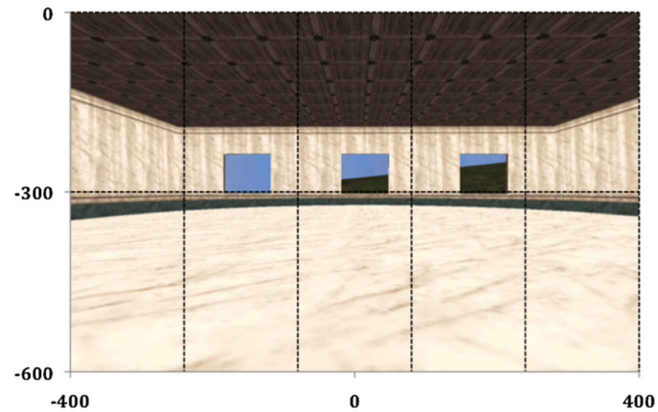

Fig. 2. Regions of interest. View of the Place maze from one of four start positions. The display was divided vertically into two regions of interest (above and below the horizon) and horizontally into 5 regions of interest (center and off-center).

would always be in the same place and that they should try to go to the platform as quickly and directly as possible. They were also informed that on one trial (the probe trial) the platform would be very difficult to find but that they should continue to search for it. Once on the platform participants were encouraged to look around the room as much as they liked, and to indicate to the researcher when they were ready to proceed to the next trial. The next trial began with no inter-trial interval. During the 50 s probe trial, no platform was present until the trial ended, at which point it rose with the usual sound.

2.3.2.4. Cue maze trials. Testing in the Cue maze consisted of 12 trials in the same pattern as that of the Place maze: 1 exploration trial, 10 invisible platform trials and 1 probe trial. In this maze there were 8 objects on the arena wall on every trial. Participants were told that the platform would change locations, but that there would always be a clue to its location. The platform moved position from trial to trial, but was always in the center of one quadrant. All objects remained in the same positions throughout testing, but the object closest to the platform was removed and the cue object (a golden urn) was put in its place to provide the only clue to the platform's location. Probe trials were completed in a manner identical to that of the Place maze.

2.3.3. Maze order

All participants received training in both Place and Cue mazes. Maze order was randomly assigned but balanced according to gender. The interval between the two mazes was 10–15 min and was filled with another spatial task that was the same for all participants.

2.4. Data analysis

2.4.1. Navigation

The latency (time to reach the target platform) was recorded for the four visible platform trials and for the invisible platform trials in both the Place and Cue mazes. This is a conventional measure used to assess learning in the virtual environments. When comparing navigational performance between the two mazes, the data from the first trial was excluded from the analysis because on this trial the participant is searching for an unknown location, whereas on subsequent trials they are returning to a place they have been and are therefore using different attentional and cognitive processes. For the probe trials, we measured the amount of time spent in each quadrant and recorded the 'dwell time' or percentage of total time spent in each quadrant with an emphasis on the southeast quadrant where the platform had been located.

2.4.2. Gaze position

Prior to any analysis, y-position data was first corrected for individual differences by adjusting each participant's data for the difference between their baseline (horizon) and the computed center of the screen (−300) so that the co-ordinate "−300" represented the horizon for every participant (Fig. 2). Except for the trial-by-trial analysis, all representations of gaze position were averages of trials 2–10, for the same reason this range of trials was used for latency.

We analyzed gaze position using a series of procedures. First we used MATLAB® routines to compute and display an 80×60 "heat map" of all participants in each condition (Place and Cue). This heat map represented the number of 60 Hz samples (60 per trial) that the participants' gaze fell within each 10×10 pixel region of the display. Next, we analyzed vertical gaze (y-position) and horizontal gaze (x-position) data separately. We averaged (baseline corrected) y-position data across trials 2–10 for each of the 60 samples collected in the first second within each condition (Place versus Cue). We also computed the average y-position within the first second of each trial for each participant. We then computed frequency histograms for the y-position data by counting the number of samples of y-position data that fell into each 5-pixel bin between the bottom and the top of the screen (−600 to 0). Finally we compared the vertical gaze sample frequency (percent) above the horizon for each participant in the Place condition to the frequency (percent) above the horizon in the Cue condition using dependent t-tests.

Analysis of horizontal gaze position focused on the frequency distribution of x-position across the display for each participant in the first second of each trial. We divided the 800 pixel-wide display area into 28 regions that were 28.6 ($\sqrt{800}$) pixels wide. Then we binned the 28 regions into five regions: far-left, left, center, right, and far right (Fig. 2). Finally, we analyzed horizontal gaze positions for the frequency of "on-center" versus "off-center" samples for each participant in both Place and Cue conditions and compared using single-sample and dependent t-tests where appropriate.

3. Results

3.1. Navigation results

Performance on visible platform trials showed that all participants were able to use the joystick and were capable of following the instructions necessary for completing the virtual maze tasks. The mean latency to the platform on the visible trials was 3.10 s (SEM = .12 s). On invisible platform trials, performance in the Cue maze was better than in the Place maze. Participants took less time to reach the platform when it was marked by a proximal landmark than when they needed to navigate using distal cues. Latency to find the platform in the Cue maze (M = 6.4 s, SEM = .52 s) was significantly shorter than latency in the Place maze (M = 9.7 s, SEM = 1.19 s, $t(20) = 2.64$, $p < .05$, $d = .78$). These times were consistent with the scores obtained in our previous experiments using similar behavioral paradigms (see for example, [24]).

On probe trials, participants demonstrated the same level of confidence as to the location of the platform after completion of both tasks. There was no significant difference in the amount of time searching in the correct quadrant during the Place maze probe trial (M = 53%, SEM = 4%) versus the Cue maze probe trial (M = 59%, SEM = 5%), $t(19) = 0.98$, $p = .33$).

3.2. Eye movement results

The eye tracking data from the first second of invisible trials 2–10 was condensed and used to create heat maps that showed the location of gaze on the screen (Fig. 3). Regions where eye tracking coordinates were more concentrated indicate areas of the screen that were looked at most often. Gaze patterns in the two mazes were very different from one another. In the Place maze, gaze coordinates were concentrated on the center of the screen and above the horizon where the windows provided a view of the outdoor landscapes. In the Cue maze, gaze coordinates were concentrated below the horizon on the three regions of the screen that corre-

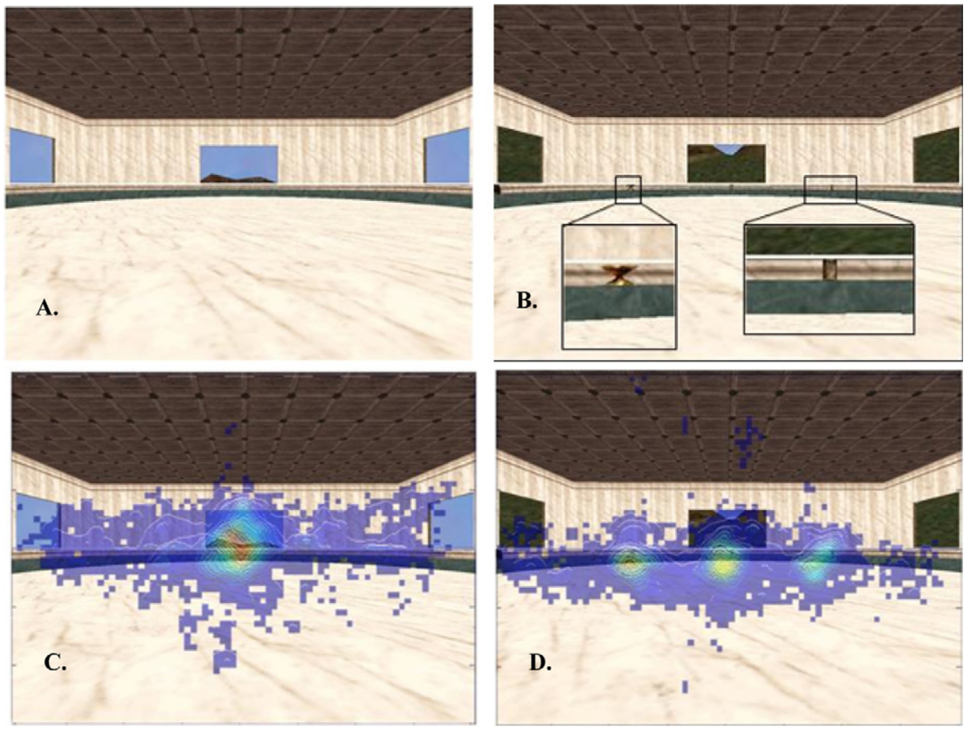

Fig. 3. Features of interest and heat maps. Views of Place (A) and Cue (B) mazes from two start positions. Insets provide greater detail of objects and show that objects were entirely below the horizon, shown here as a white line (not present during testing). Heat maps indicate the predominance of gaze in Place (C) and Cue (D) mazes during the first second of invisible trials 2–10. Hotter colors indicate greater frequency of gaze in 10×10 pixel regions of the display.

sponded to the three objects located atop the arena wall that were visible at the start of each trial.

Fig. 4 depicts the average gaze over the first second of invisible trials 1–10 in the two conditions, clearly showing an upward arch followed by a down turn under both conditions, but with greater time spent above the horizon in the Place maze. Fig. 4 also shows that gaze above the horizon in the Place maze, or towards the horizon in the Cue maze was sustained only very briefly, on the order of 0.5 s. The data also indicate that the participants were able to orient to the environment at the start of the trial within the first quarter second (by sample 15). Preliminary analysis of longer sampling durations at the start of trials showed no consistent tendency for participants to look up again. These data indicate that information crucial to orientation at the start of trials was captured very quickly.

On the first trial in both Place and Cue mazes, participants gaze remained well below the horizon (Fig. 5). On the second and all subsequent trials, gaze was higher in the Place maze than the Cue maze (Fig. 5). The change in gaze position from trial 1 to trial 2 was significant in both mazes (Place: $t(20) = -4.91$, $p < .0001$; Cue: $t(20) = 2.83$, $p < .01$), indicating that it only took one trial for participants to learn to look at different regions of the screen for Place and Cue mazes. Most importantly, when gaze positions from trials 2–10 were averaged across trials, the gaze position in the Place maze ($M = -290$, $SEM = 6.6$) was significantly higher than in the Cue maze ($M = -311$, $SEM = 4.5$), $t(20) = 4.37$, $p < .0001$, $d = 0.81$. These data indicate that in the Place Maze, gaze was directed more towards the upper portion of the screen containing the landscapes than in the Cue maze, where gaze was focused in the lower portion of the screen containing the objects. The lack of difference in gaze positions on the first trial, and presence of a difference on the second trial indicates that the difference was not due simply to differences in the stimulus properties of the Cue maze (i.e., the cue objects) but rather were due to a learned difference as to which stimuli were most relevant in each maze.

Participants appeared to learn to attend different regions of the virtual environment before they learned where to find the platform. That is, gaze position stabilized much more quickly than did latency to find the platform (Fig. 5). Note that the latency data was more variable than gaze position and took longer to reach asymptote. Although latency to the platform does reach asymptote by the 10th trial, eye movements indicate behavioral differences much earlier (i.e., by the second trial). This suggests that eye movements are a particularly early measure of strategy selection, and that strategy selection precedes sure knowledge of the platform location.

Fig. 6 illustrates the frequency distribution of gaze positions in Place and Cue mazes, in 5-pixel bins. During the first second of trials 2–10 in the Place maze, gaze was more frequently above the horizon than below it. In the Cue maze, gaze was more frequently at or below the horizon. When measured as percentage of the first second spent above the horizon, participants spent significantly more time looking above the horizon in the Place maze on invisible trials 2–10 ($M = 61\%$, $SEM = 6.4\%$) than the Cue maze trials 2–10 ($M = 32\%$, $SEM = 6.5\%$, $t(20) = 4.33$, $p < .0001$, $d = 0.97$ (Fig. 6). These differences were not dependent on the order in which the mazes were presented.

Horizontal gaze positions also varied according to maze type. Fig. 7 shows that gaze was distributed uni-modally in the Place Maze and tri-modally in the Cue maze. This provides a clearer picture of gaze distribution consistent with the heat map (Fig. 3) which showed the 3 modal positions to be right on the positions of cue objects on the display at the start of each trial. For statistical analysis, the eye tracking data for the Place and Cue conditions were binned into five regions (Fig. 2) and then collapsed into on-center and off-center regions. We compared the percentage of off-center gaze both within and between the maze conditions (because the sum of on-center and off-center gaze always equals 100%).

During the first second of each trial, participants looked more in the center of the screen while navigating in the Place maze whereas

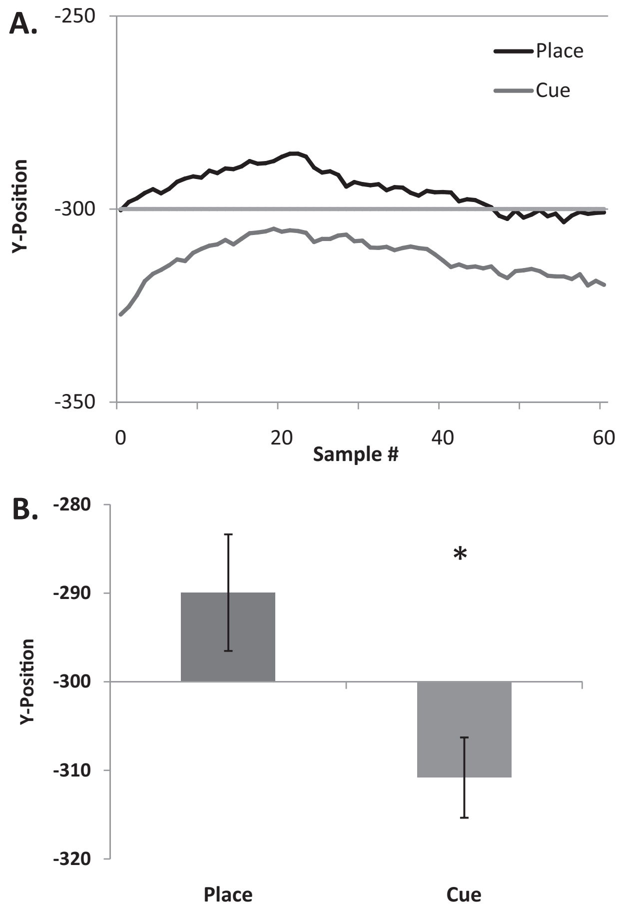

Fig. 4. Gaze dynamics. (A) Average gaze position across the 60 samples of the first second of trials 1–10 in Place and Cue mazes. The line at −300 marks the position of the horizon. (B) Average gaze position in Place and Cue trials 2–10. $^*p < .05$.

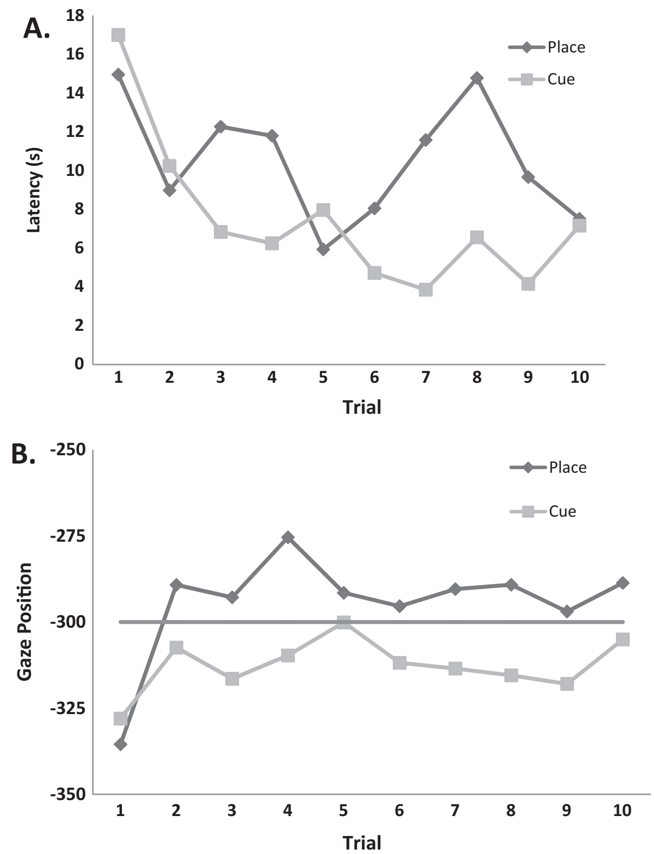

Fig. 5. Navigation and gaze position. (A) Average latency to platform across trials in Place and Cue mazes. (B) Average gaze position across trials in during the first second of each trial in Place and Cue mazes. The line at −300 indicates the position of the horizon.

their gaze was more distributed (towards the proximal cues) while navigating in the Cue maze (Fig. 7). The percentage of gaze in the off-center regions was significantly greater in the Cue Maze than in the Place Maze, $t(20) = 7.55$, $p < .00001$, $d = 2.30$.

4. Discussion

The present results provide evidence that in an appropriately designed virtual environment, a simple eye-tracker can provide data that can be easily analyzed to identify which navigational strategy participants are using to navigate in virtual space. Heat maps of gaze position indicated qualitatively that during orientation in an allocentrically biased environment (the Place maze), gaze is predominantly central and above the horizon, whereas in an egocentrically biased environment (the Cue maze), gaze was focused on three laterally distributed points corresponding to the positions of cue objects proximal to the target location. The average gaze position in the first second of trials indicated that participants captured the environmental information necessary for orientation at the start of each trial very quickly, within the first half second. Assessing the percentage of gaze position above the horizon trial-by-trial showed that participants quickly learned where to look to find the information most crucial to their current navigational strategy. This attentional shift occurred after just one trial, well before participants were able to display accurate knowledge of the platform position.

In other words, there was a clear difference in gaze position in the allocentrically and egocentrically biased mazes. This difference corresponded to the different environmental features necessary for optimally navigating each maze and the difference was learned rather than being driven by the stimulus features of the environment. Although it is not surprising that participants navigating egocentrically would immediately attend to egocentric navigational cues to orient, one could imagine a different scenario in which participants first orient themselves to their position in the room (using allocentric cues) and only then look for egocentric navigational cues. However, the present data clearly discount this possibility. Therefore, these findings support the conclusion that in environments where egocentric and allocentric navigation cues are spatially distinct, gaze position can be used to identify which navigational strategy a participant is using at least during the first second of orientation.

There are several alternative interpretations of the data that should be considered. First, it could be argued that the difference in attention between the Place and Cue mazes was due to the visual difference in the appearance of the two mazes; that is, the gaze was drawn below the horizon by the cue objects, which were not present in the Place Maze. However, this interpretation seems unlikely in light of the data showing that on the first trial, when the cue objects were most novel and most likely to gain attention, there was no difference in gaze position between the Place and Cue Mazes. Rather, it appears that the gaze positions were different because participants were using different stimuli to navigate by, and did so because of the behavioral contingencies. That is, they looked at objects when the objects predicted the platform location, and looked at the landscape when these features predicted the location of the platform.

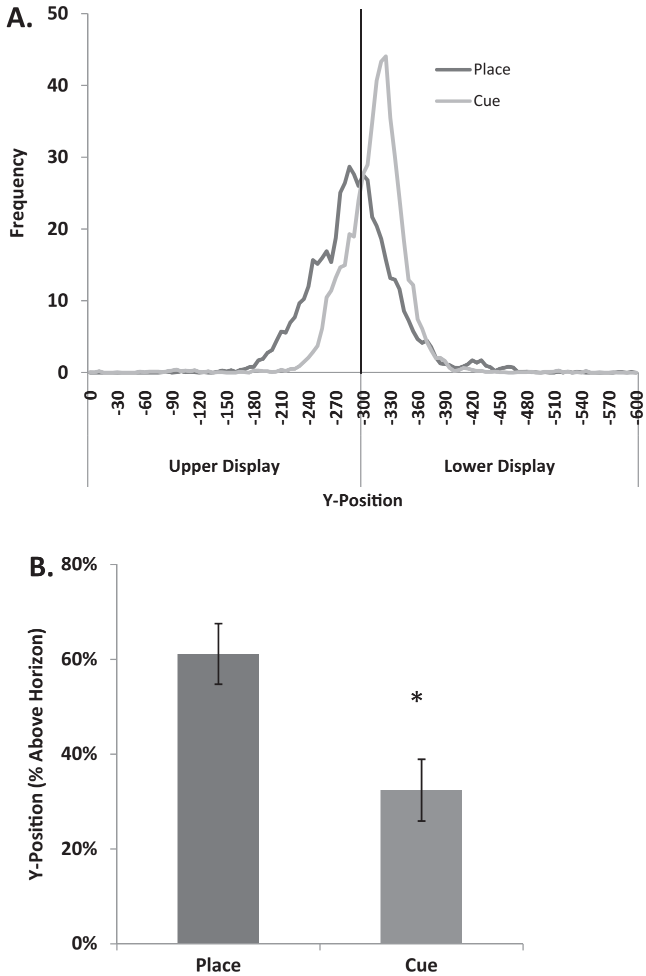

Fig. 6. Vertical gaze position. (A) Histogram comparing the vertical distribution of gaze in Place and Cue mazes during the first second of trials 2–10. Vertical line at −300 marks the position of the horizon. (B) Percentage of gaze above the horizon in Place and Cue maze trials 2–10. $^{*}p < .0001$.

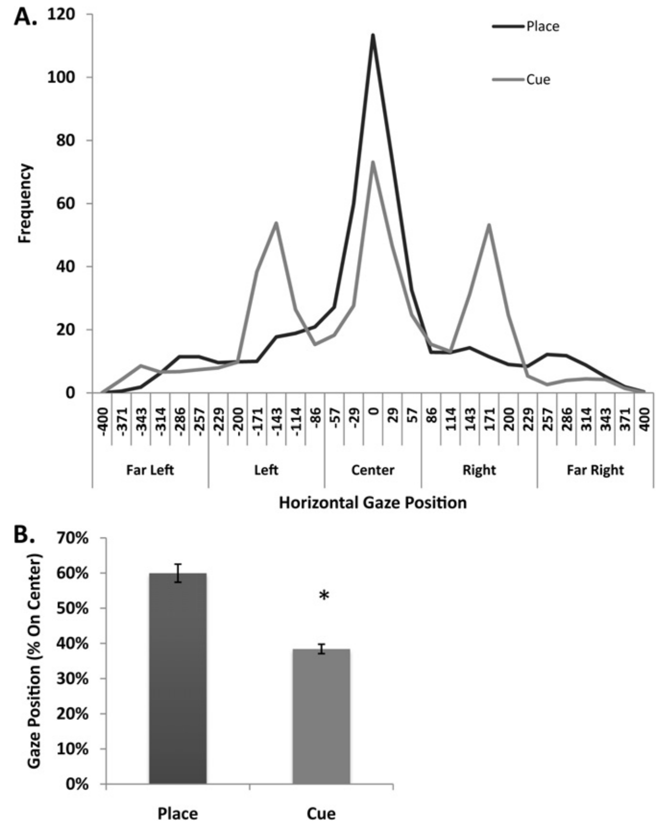

Fig. 7. Horizontal gaze position. (A) Histogram comparing the horizontal distribution of gaze in Place and Cue maze trials 2–10. Center of the display is at 0. (B) Percentage of gaze on center fifth of display in Place and Cue mazes during the first second of trials 2–10. $^{*}p < .00001$.

In a similar vein, it could be argued that even though participants were looking in different places in the environment, they were not necessarily navigating by these different stimuli and therefore, the gaze position was not indicating navigation by two different strategies. This argument is based on the premise that the stimuli in these environments were capable of supporting either or both strategies simultaneously and that the participants were not "forced" into the intended mode of navigational cognition. However, this argument also seems untenable because both mazes are designed such that they can only be solved efficiently using a particular strategy [8,25]. Remember, in the Cue maze, the platform moved to a different quadrant on each trial, making it very inefficient to solve allocentrically. Because the latency data showed that both mazes were solved efficiently, it is reasonable to conclude that both mazes were solved using the appropriate strategy, with the proximal objects being used in the Cue maze and the configuration of windows and landscapes being used in the Place maze.

Finally, it could be argued that since the participants were moving, then they were not necessarily looking at the environment as first presented at the onset of each trial (*viz.*, static view from the start position) and therefore were not looking at the environmental features we think they were. However, this argument is not supported due to three factors: the characteristics of the maze, the data collection and the results. First, the landscapes were above the horizon regardless of where the participant was moving in the maze, so it made no difference as to whether they were moving. Second, gaze positions were collected only during the first second, and analysis of the latencies to start (data not shown) indicated that participants took more than a second to begin moving on 89% of trials in the Place maze, and 86% of trials in the Cue maze. Third, movement during the first second, if it resulted in a displacement of environmental features on the display screen, would have had the effect of blurring (or broadening) the localization of gaze position. Whether this happened or not is moot because the analysis of the gaze position data indicated clear localization of gaze near the stimulus objects in the Cue maze, and in the upper central portion of the screen in the Place Maze. If there had been too much movement in the period of analysis, this analysis would not have been successful.

A few studies have previously demonstrated the value of analyzing eye movements in navigation research. Jin et al. [26] tracked eye movements while participants were driven passively through a dynamic virtual environment and asked to memorize a route, and then, while they were looking at static images, to make (but not execute) navigational decisions. They found that participants' gaze was focused significantly more on landmarks that predicted location. While promising, this methodology is not applicable during the dynamic feature changes and decision-making of active navigation. In a recent study, Hamilton et al. [27] examined eye movements in an allocentric virtual MWM. They found that participants who looked at allocentric room cues early in the trials were those who took the most direct paths to the platform and were therefore classified (by the authors) as "allocentric" navigators. Their analysis was similar to that of the present study, though more complicated and not as objective. They did not analyze eye movements in an egocentrically biased environment and could not perform a trial-by-trial analysis to see how gaze patterns changed over learning.

We believe that gaze position analysis as described here represents a significant advance in methodology for analyzing behavior. It is simple, relatively inexpensive and can therefore be used by a large number of investigators. Previously, analysis of attention in virtual (or real) environments during navigation was difficult because of the amount of computation required to track gaze fixation relative to a million or more pixels that changed 30 times per second. Even reducing the 3D environment to a 2D wire frame [27] still requires considerable computational power and expertise. We are happy to enter into collaborative relationships with researchers wishing to use the virtual environments and/or the camera system and analysis software described here (contact corresponding author).

A key aspect of the methodology in this study is the combination of simple gaze position analysis with virtual environments designed to separate egocentric or allocentric cues along the horizontal or vertical dimensions. As long as the stimuli are spatially separated vertically or horizontally (or both), the current methodology could be used to identify which stimuli are being used by participants under different circumstances or to identify the specific times during trials when participants are attending to navigational stimuli, and are therefore processing navigational information and computing future navigational responses. Therefore, this methodology is not restricted to just our mazes, or even to virtual water mazes. It could easily be used in radial arm mazes or city-scape mazes (though perhaps not in corridor mazes). Furthermore, the present methodology clearly has the potential to provide for trial-by-trial analyses throughout the session, or analyze gaze beyond the first second though we did not have a sufficiently large n in this experiment to do so. Commercially available eye-tracking systems have the potential to provide information about gaze position with higher spatial and temporal resolution than our system, though clearly our system was sufficient to the task at hand.

The ability to know exactly when a person is thinking about navigational stimuli has great potential for studies relating neural activity to navigational cognition. Brain imaging (including fMRI) has already been used with great success to identify neural correlates of navigation [1,28] but it is not always clear what strategy is being used at any given time, except through laborious analysis of self-report [28]. However, self-report is unavoidably subjective and necessarily obtained well after the navigational task, leading to potential memory errors inherent in any reconstructive recall. The addition of eye tracking to fMRI could represent a significant advance in the ability to associate activity in particular structures with fleeting moments of attending to environmental stimuli when the environment is organized so that objects required for different strategies are located in different regions of the display. The technique could also be applied to the analysis of EEG in a manner similar to the analysis of event-related potentials (ERP) with signal averaging synchronized with cognitive states (as indicated by eye movements) rather than sensory events.

We plan to extend the present results and refine the methodology. First, with a larger sample size, we will investigate whether *x*- or *y*-position data or a combination of the two, is better able to discriminate strategies on a case-by-case and trial-by-trial basis. Second, while data volume remains challenging, we plan to extend the analysis beyond the first second to see how gaze patterns develop beyond orientation and throughout each trial. However, this has lower priority since Hamilton et al. [27] have already demonstrated that gaze after the start of each trial in a virtual water maze is directed primarily, if not exclusively at the floor, at least by those participants capable of competent allocentric navigation. Third, we plan to use the technique to investigate factors controlling spontaneous strategy selection and strategy switching. That is, we will attempt to answer questions of how quickly strategies are adopted in an environment that provides features suitable for either egocentric or allocentric navigation, and once adopted, do participants switch from one strategy to another. Finally, we plan to apply gaze position detection of strategy to the question of gender differences and the relation between strategy selection and navigational performance.

In conclusion, gaze position analysis shows much promise as a research tool in the area of spatial navigation. In combination with an appropriately designed virtual environment, it is a simple, efficient means of identifying and characterizing navigational strategies early during testing, as well as during locomotion within trials. Application of this analysis would be particularly useful to identify what strategies are being used in environments that provide both proximal and distal cues, which is commonly the case in the real world. Replication across different navigational tasks in both real and virtual environments would demonstrate the reliability of using eye tracking data for inferences about the way people are navigating, and furthermore, would promote a better understanding of the relationship between eye movements and spatial cognition.

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