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Effect of visual cues on human performance in navigating through a virtual maze

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Abstract

Navigation in Virtual Environments (VEs) requires users to develop spatial knowledge of the environment primarily through visual cues provided to the user. Thus, the design and display of visual navigation cues is important for efficient navigation in a VE. In this paper, we report the results of an experiment in which three different visual cues were tested for their benefit toward users' navigation in a 3D virtual maze. The experiment varied the form of visual cue: a 2D map, a 2D map with a directionally ambiguous cue, and a 2D map with a directional cue. Eye tracking data was collected and analyzed to examine the correlation between the type of visual cue presented and the navigational efficiency of the user through the virtual maze. It was observed that the cue type affected performance of the participant in the 3D maze. The directional cue was most effective in the time taken by users to reach the center of the maze. Results of this study have implications for VE design as well as for game development.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Applications of Virtual Reality, Interaction Techniques and Devices, Human Factors]:

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1. Introduction

Virtual Reality (VR) is an artificial environment that is experienced through sensory stimuli provided by a computer. In such environments, the user's actions partially determine what happens in the environment. With recent advances in technology, VR is being increasingly utilized in a wide range of applications such as avionics, visualization of architectural modeling, and games. Users navigate these spaces through immersive interfaces. However, not much work has been done examining the usability and adaptability of these interfaces. A relevant area of interest that was investigated by Vila et al. [VBA03] was that of human navigation and wayfinding in VR. Having a better understanding of navigational patterns employed by humans while interacting with these environments will enable software developers to design more intuitive and effective VR interfaces.

Previous research on spatial cognition and human psychology has examined the perceptual skills needed during navigation [Gol99]. There is significant variation between individuals in a variety of spatial behaviors, and it is a challenge to identify the sources of this variation [WHK98]. Goldin and Thorndyke [GT82] examined different types of knowledge developed from a direct navigation experience and from a simulated experience. The results of the study indicated that people could learn about environments from a simulated medium such as film. They suggest that interaction, either by a person driving the tour or interacting with the environment in a simulation, might show different results. The results of this study also show that within a condition, such as the film condition, adding an additional navigational aid has consequences and that they are task dependent. In one case a map or narration can hinder performance, while in another a map improves performance while narration lowers it. These results are important when deciding what aid to use to introduce someone to a new environment.

Streetar et al. [SVW85] performed a wayfinding study comparing navigational aids for people driving in a car. This

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study showed that during wayfinding, it is more difficult to interpret a map than it is to receive directions. The finding that the combination of tools did not produce better performance than the narrative alone is important, since more tools may not mean better performance.

Regian and Shebilske [RS90] conducted studies of the use of VR as a training medium for visual-spatial tasks. One of their experiments involved wayfinding. The environment used in the wayfinding study was a virtual maze. The authors conclude from their results that subjects can learn spatial-navigational skill in a Virtual Environment (VE). However, their design and methodology may not necessarily support this claim. Previous research has already shown that "people do not act like randomly moving automata that make unbiased decisions at each point where a decision has to be made" [PZC90]. Two rules that Peponis et al. observed in wayfinding behavior are that people avoid unnecessary backtracking and tend to find the area that gives them the best visual access to other areas. Regian and Shebilske may have, for example, run a control group for the same wayfinding task that could have had no experience in the building, and therefore would have had to search for the given unique object using strategies that would probably be much more efficient than a random search.

The wayfinding literature indicates that receiving directions verbally or through signs is advantageous when trying to find a goal. In contrast, the use of maps can be disadvantageous. Darken et al. [DS93] reported on an informal study looking at toolsets for wayfinding in Virtual Environments. The tools available to the participants were flying (the ability to rise above the VE), spatial audio markers, visual markers (breadcrumbs), coordinate feedback, grid navigation, and two map-views of the world. Informal observations indicated that people used the different tools in a variety of ways. Their conclusion was that subjects showed different behaviors when they used different tools in wayfinding.

The literature on navigation and wayfinding indicates an uncertainty for effective means of introduction of a person to a new environment, so that they will gain navigational awareness efficiently. Studies show that exposure time and navigational tools can affect the process [THR82, GT82]. These studies revealed that map study before entering an environment can be beneficial but that when used alone it does not provide complete navigational awareness. The research also points out that depending on the type of introduction to an environment, an additional navigational aid can have a positive or negative effect on the task being executed. The results show that learning of an environment can occur without actually being there, but the results do not reveal whether it is better to be an active participant or a passive observer when being exposed to a new environment.

The wayfinding literature also shows that people are better at finding a target location when using signs or narrative directions than when using maps. The literature also shows that given a choice, people prefer shorter routes to longer routes, despite the complexity of a shorter route. Ruddle et al. [RPJ97] investigated the effects of landmarks on route-learning ability and other spatial cognition tasks. They observed a slight improvement in the time taken to complete the task in the environment containing landmarks in contrast to the environment without landmarks. However, when performing distance and orientation estimates, the effect of the inclusion of landmarks in the environment appeared to be negligible. In contrast to this outcome that only weakly suggests that landmarks play a role in wayfinding, subjects reported in questionnaires that they actively used the landmarks, particularly in forming associations with specific locations in the world.

Thus, there appears to be a need for further examination of beneficial navigational aids to a user, particularly when introducing the user to a new environment, during initial exposure and following exposure, when the aid is no longer available. One way to measure the effectiveness of navigational aids such as maps in Virtual Environments is by eye tracking. By analyzing what the user is looking at when navigating through a VE, we can measure the relative use of the navigational tool. The eye tracking study presented in this paper paid particular attention to human performance and the subject's ability to find their way using visual cues (feedback). It also presents the importance of spatial knowledge. Speed of task performance was used to measure the effect of visual cues on transfer of spatial knowledge. In this case, speed was measured as the time required to search and identify the route needed to reach the center of a virtual maze. This study also conducted subjective evaluations of visual cues used for the experiment. One important issue surrounding the use of visual cues was the type of cue that the participants found most useful in navigation and determining the format for presenting this visual information in a way easy to interpret and utilize.

2. Methodology

The goal of the experiment was to test the importance of visual cues in helping users navigate through a virtual maze. The cues presented were either simple 2D map (No Cue), 2D map with directionally ambiguous cue (Dot) or 2D map with directional cue (Arrow). The latter two form of stimuli are shown in Figure 1. The visual map cue (3 levels) acts as the independent variable in the 3-factorial between-subjects design used in the study. Our study was based on the following hypothesis (H_0): There is no effect of visual cues on human performance in the virtual maze.

2.1. Equipment

The computer used for rendering the VE was a 1.5 GHz dual-CPU Linux PC with 1 GB RAM and a NVidia GeForce4 Ti 4600 graphics card. Multimodal devices include a V8 Virtual Research Head Mounted Display (HMD) and ISCAN

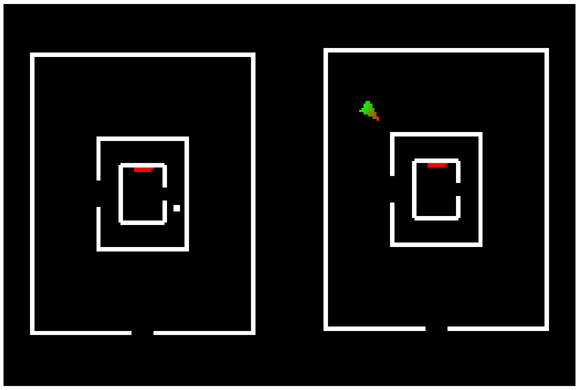


Figure 1: *Different visual cues on 2D map for the subjects.*

video-based corneal reflection eye tracker. The V8 HMD offers a 640×480 pixel resolution for each eye, with separate video feeds for the left and right eye. Eye tracking is provided by the ISCAN eye tracker unit mounted within the HMD. Each of the eye trackers is composed of a miniature camera and a pair of infrared LEDs. The ISCAN RK-726PCI High Resolution Pupil/Corneal Reflection Processor uses corneal reflections (first Purkinje images) of the infrared LEDs mounted within the helmet to measure eye movements. The processor operates at a rate of 60 Hz (30 Hz when both eye movements are tracked) and the subject's eye position is determined with an accuracy of approximately 0.3 degrees over a 20 degree horizontal and vertical range using the pupil/corneal reflection difference. The maximum spatial resolution of the calculated Point of Regard (POR) provided by the tracker is 512×512 pixels per eye. The HMD and the eye tracking cameras are shown in Figure 2.

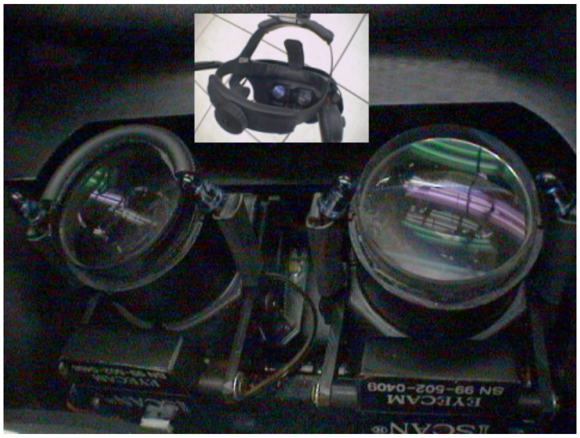


Figure 2: *Head-mounted display with binocular eye tracker.*

HMD position and orientation was measured using Ascension Technology's 6 Degree of Freedom (6 DOF) Flock of Birds electromagnetic tracker, with the position/orientation sensor mounted on the top of the HMD as shown in Figure 3. A 6 DOF mouse was used for user navigation.

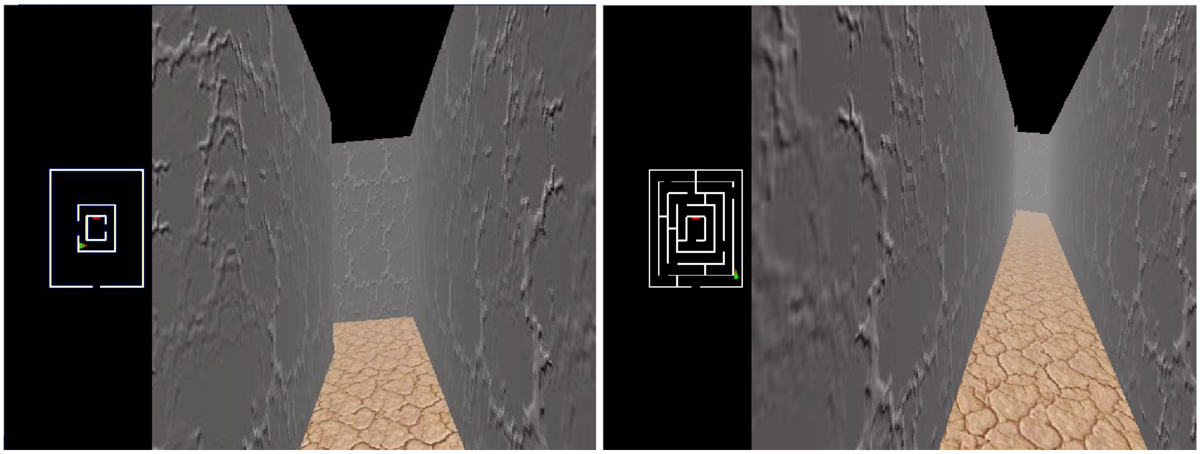
Figure 3: *Virtual Research V8 Head Mounted Display and 6 DOF mouse.*

2.2. Subjects

Initially, 24 subjects were drawn from a population of graduate and undergraduate students at Clemson University and were randomly assigned to only one of the three condition groups (each condition being one form of visual map cue). Of the 24 subjects tested, 9 subjects were excluded from the statistics due to eye tracker error. Eye tracker error was estimated by asking the subjects to fixate on the search target in the 2D map (Mona Lisa image represented by a red bar, as shown in Figure 1). If the subject's real-time gaze fell outside the 2D map (50 or more pixels away from the target), their eye movement data was not used in the study. Since the HMD provides a field of view of $75.3^\circ \times 58.4^\circ$ visual angle [WWH97], our eye tracker error threshold for exclusion was approx. 6°. Eventually, 15 subjects (8 M, 7 F) completed the study, with 5 subjects randomly assigned to each of the 3 condition groups. The distribution of gender across the 3 condition groups is not uniform: No Cue: 2 M, 3 F; Dot: 2 M, 3F; Arrow: 4 M, 1 F.

2.3. Design

Subjects in each of the three groups were given the opportunity to familiarize themselves with the environment and the screen elements during the experiment phase. Note that the same maze was shown to all the subjects in order to eliminate treatment variability. Consequently, we adopted a between group testing strategy to minimize learning effects. Also, none of the users were allowed to view the maze used in the actual test phase before it had begun.



(a) VE for familiarization.

(b) VE for testing.

Figure 4: *Virtual maze for familiarization and testing.*

All subjects had to perform the same task in the VE using the maze i.e., reach the center of the maze. Through the HMD, they saw a 640×480 window split vertically into 2 regions (see Figure 4). On the right side of the screen was the 3D maze that the subjects were navigating. The left side of the screen displayed a 2D top-view of the same maze.

The first test group was the control group. This group was asked to navigate through the 3D maze and reach the center with no visual cues other than the 2D map on the left.

The second group also performed the same task. A directionally ambiguous cue in the form of a small dot was provided in the 2D map, which represented the location of the subject in the 3D maze (see Figure 1). The subject was able to use this as a point of reference while traveling through the maze. The location of the dot updated in real-time as the subjects moved through the maze.

The third group was provided a directional cue (an arrow) within the 2D map. The arrow pointed in the direction the subject was looking (see Figure 1). In addition to their location, this gave them a sense of orientation, as they knew which direction they were facing inside the 3D maze. Like the dot, the arrow also updated in real-time as the subjects moved through the maze.

The subjects were timed from entering the maze to completion. Their eye movements were recorded every 40 ms and stored in a Point of Regard (POR) file. The POR file is an ASCII file containing the (x, y, t) POR coordinates as measured by the eye tracker, along with a data timestamp. This POR file was used in the offline analysis phase to ascertain how often the subject used the 2D map and to determine if there was a correlation between the different cues and time taken to reach the center of the maze.

2.4. Procedure

Each trial, including pre-test, test and post-test, was completed by each subject in approximately 30 minutes.

1. **Pre-test**: The subject was asked to read and sign an Informed Consent Form detailing the experiment objectives, benefits and possible risks. Demographic data related to age, vision, and experience with VR equipment was also collected. Subjects were asked if they had any questions before the experimentation phase.

   Next, subjects were fitted with the HMD, handed the 6 DOF mouse, and were familiarized with movement and navigation in the virtual maze. A simple version of the maze was presented to the user as shown in Figure 4(a). This provided a learning opportunity for the user to work in tandem with the cues and the 3D world. Users were not timed during this phase. We adopted a modified head-directed navigation method proposed by Fuhrmann et al. [FSG98] for navigating the virtual maze. Subjects were verbally instructed that the left button presses of the mouse would allow them to move forward along the line of view while the right button presses would allow them to move backward along the direction of view. To change the direction of motion, they were asked to turn their head in the appropriate direction.

   On completion of this phase, users were asked 3 pre-test questions, listed in Table 1, to gauge their initial reaction to the visual interface.

2. **Test**: This procedure was divided into two phases:

   a. Calibration: To obtain proper overlay of the eye tracker coordinates on the graphics screen, we calibrated the eye tracker. Five squares were displayed

Category	Pre-test	Post-test
Design	1. The location of the 2D map is appropriate. 2. The visibility of the display is good. 3. The colors used on the display are pleasing to the eye.	1. The location of the 2D map was appropriate. 2. The visibility of the display was good.
Usefulness		1. The 2D map was helpful in finding Mona Lisa. 2. The visual cue presented in the 2D map was helpful in navigating the maze.
Eye Tracking		1. I was comfortable with the eye tracking gear. 2. I would have performed better with different eye tracking gear.
Frequency		1. How often did you use the 2D map in the maze?

Table 1: *Pre- and post-test questions.*

in sequence on extant screen locations on which the user was asked to fixate while the operator calibrated the eye tracker. (The head tracker does not require calibration.)

b. Test: This was the main test scene for the program. The visual cues presented to the user were the same as in the familiarization phase. All the subjects were instructed to traverse from the entrance of the maze to the center of the maze, represented by a horizontal red line in the 2D map (a picture of the Mona Lisa in the 3D maze). Subjects were timed as soon as the test scene started and their eye movements were recorded for later offline analysis. The test screen is shown in Figure 4(b).

3. **Post-test**: Upon successfully completing the experiment, the subjects were asked to complete a questionnaire related to the task they had just performed. All responses were on a 5 point Likert scale. The questions were divided into 4 categories. Post-test questions asked are given in Table 1.

2.5. Role of eye tracking in the experiment

Subjects' fixations and saccades were studied to determine how often they used the 2D map and if there was a correlation between the different visual cues and the time required to navigate through the maze. We recorded only the left eye data, assuming that both eyes of the user move in tandem.

We hypothesized that subjects without any visual cues would make significantly more fixations over the 2D maze and would rely more on their cognitive ability to navigate. In the second test group, we expected that there would be significantly larger number of switching eye movements (saccades) between the 3D view and the 2D view, partly because of the lack of orientation information. In the third test group, we expected that there would be a smaller number of fixations on the 2D map and faster navigation through the maze since we expected the third group to predominantly fixate the map at the beginning of the test program to chart out a predetermined course. This would be followed by rather fast "glances" at the 2D map to make sure that the subject was following the predetermined path.

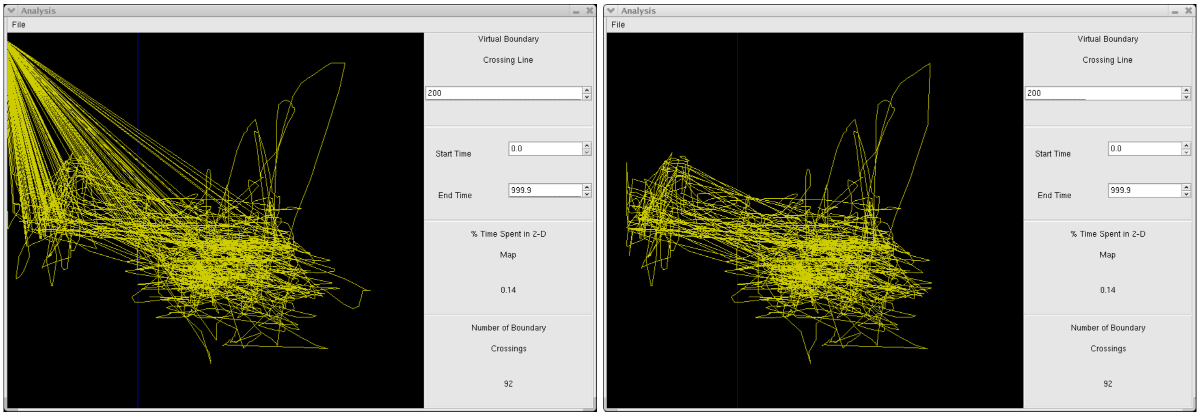
2.6. Analysis of eye tracker data

For measuring the number of eye movement crossings that the subjects made when shifting their gaze from the 3D to the 2D map and vice versa, we used a simple eye movement analysis program. Figures 5 and 6 show examples of recorded eye movements superimposed on the environment, and raw and denoised eye movements in the off-line analysis program, respectively.

The off-line analysis program was developed to measure the number of crossings from the 3D to the 2D view, as well as the percentage of time spent in the 2D view. Eye tracker coordinates beyond a clipping region were discarded due to the mapping limitations of the eye tracker and the loss of eye tracker data during blinks. The analysis program also contains a movable "virtual vertical line" acting as the boundary between the 2D and the 3D view. Since the screen was 640×480 pixels in dimensions, with the 2D map occupying 160×480 pixels, a virtual line of 200 pixels from the left was chosen to represent the boundary.

2.7. Coordinate mapping for the eye tracker

One of the critical issues in using the eye tracker is to obtain a good mapping between the eye tracker coordinates and the application program's frame of reference. In practice, the usable eye tracker coordinates are limited by the size and the



Virtual Boundary Crossing Line: 200

Start Time: 0.0

End Time: 999.9

% Time Spent in 2-D Map: 0.14

Number of Boundary Crossings: 92

Virtual Boundary Crossing Line: 200

Start Time: 0.0

End Time: 999.9

% Time Spent in 2-D Map: 0.14

Number of Boundary Crossings: 92

(a) Raw eye movement data.

(b) Denoised eye movement data.

Figure 6: *Analysis program for measuring gaze boundary crossings and time spent fixating the 2D map.*

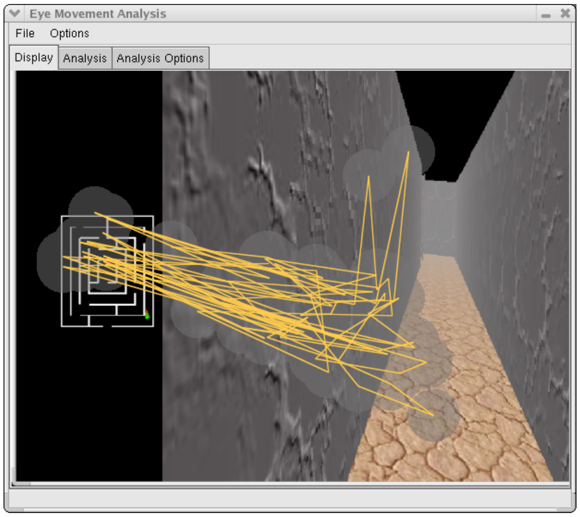


Figure 5: *Analysis program with scanpaths superimposed on a screen capture of the maze.*

position of the application window. To obtain the extents of the application program's window in the eye tracker's reference frame, the application window's corners are measured using the eye tracker's movable cursor. This is accomplished by using the fine and coarse cursor movement and noting down the cursor location readout from the screen. Given the size of the eye tracker screen reference frame (512×512) and the size of the application program's window (640×480), linear interpolation was used to map the screen coordinates of the raw POR data (cf. [Duc03]).

3. Results

One-way ANOVA between subjects (both M & F) on mean completion time (see Figure 7) suggests that the effect of visual map cue is significant, F(2,14) = 5.29, $p < 0.05$.

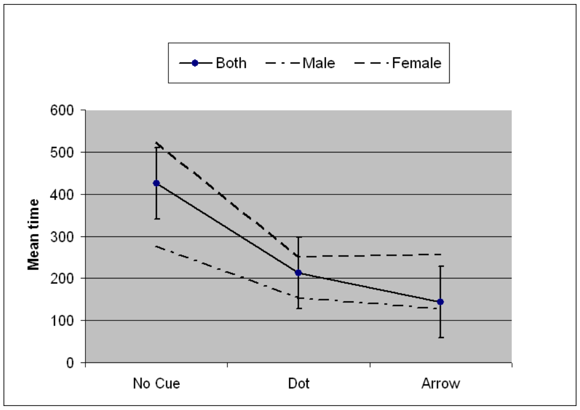


Figure 7: *Mean completion times (sec.).*

Table 2 shows the percentile data for the answers on the pre- and post-test questions provided by the subjects. The pre-test questionnaire included only design related questions and were similar to the post-test design questions. These questions were used to evaluate the subjective rating of the maze early on. Comparison of the pre- and the post-test design questions allowed us to gauge if there was any change in their rating. Only a small change in the percentile ratings was noticed. A high percentile of subjects strongly agreed on the design (45%) and usefulness (66%) of the VE. There were some general complaints with using the eye tracking gear (see Section 4). This can also be seen in the post-test eye tracking questionnaire data in Table 2.

Question Categories	SD	D	N	A	SA
Pre-test Design	0	13	17	35	52
Post-test Design	0	19	19	44	45
Post-test Usefulness	6	0	16	23	66
Post-test Eye Tracking	13	27	33	27	13
	VR	R	S	O	VO
Post-test Frequency	0	6	0	19	88

5-point Likert scale (Strongly Disagree,…,Strongly Agree)
5-point Likert scale (Very Rarely,…,Very Often)

Table 2: *Subjective questionnaire responses (percentages).*

Post-test frequency responses regarding self-reported perceived 2D map usage (last row of Table 2) reveals that the subjective rating of the majority of the subjects (88%) 'Very Often'. It is interesting to compare this subjective rating to the actual percentiles collected from the eye tracking analysis. The mean percentage of time that the subjects spent looking at the 2D map for each cue group is as follows: No Cue: 17%; Dot: 18%; Arrow: 36%. While the majority of responses was 'Very Often' or 'Often', the largest percentage of time spent looking at the 2D map occurred in the Arrow condition.

Note that mean percentage time spent looking at the 2D map multiplied by mean completion time (seen in Figure 7) yields mean time spent looking at the 2D map, i.e., No Cue: 73 sec.; Dot: 35 sec.; Arrow: 57 sec. Although this absolute metric of time spent looking at the 2D map suggests most time spent looking at the 2D map in the No Cue condition, subjects also took the most time to complete the task in this condition. In terms of actual use of the 2D map for completion of the task, the relative metric (percentage time spent looking at the 2D map) is more telling than the absolute measure.

The relative (percentage) data suggests that subjects with visual cues (particularly the directional cue) spent a higher percentage of time looking at the map. However, the relation is not significant ($p = 0.061$). Further examination of the relationship between eye movement boundary crossing and cue type by Pearson correlation, $r = -0.42$, $p = 0.12$, indicates an inverse trend between boundary crossings and cue types, i.e., as the cue changed from none to a dot to an arrow, the crossings decreased. Although not statistically significant, this trend was contrary to our expectation. We expected the control group (No Cue) to spend more time looking at the 2D map than the other two groups.

Comparing mean task completion times by gender (again see Figure 7) shows that, as expected, the mean time spent in the maze was highest for the control group and lowest for the group which received the directional cue. Interestingly, on average, male subjects took less time than female subjects. Post-hoc analysis reveals that the Pearson correlation between gender and completion time, $r = -0.56$, $p < 0.05$, is significant, suggesting that if an individual is male, he is likely to take less time to complete the experiment. Pearson correlation between VR experience and completion time is not significant, $r = -0.11$, $p = 0.7$, suggesting that experience using VR equipment did not have an appreciable effect on performance.

4. Discussion

Overall, subjects made good use of the 2D map. However, it was often noted that subjects with the visual cues of the dot or the arrow would use the 2D map to navigate through the 3D maze without looking consciously at the 3D maze. Consequently, it was observed that participants would walk the 3D maze looking at the floor. This blind navigation could be attributed to the over-reliance of the participants on the 2D map and the simplicity of the 3D environment.

Through questionnaires the participants expressed their comments on the experiments and the cues provided. The general response to the color and design elements was positive. Subjects complained about the inconvenience caused by tethered cables (a common complaint of HMDs). A few subjects mentioned that this distraction would often result in their loss of orientation within the maze thereby causing them to lose time. This would be particularly problematic for a participant who was working with no cues. The heat from the HMD was a common complaint made by all the subjects. There was disagreement between subjects on the use of the mouse in the study. Some felt it was very useful although they did not like the fact that the left mouse button would lock in a pressed position. Other groups of participants felt that the mouse buttons did not necessarily match up with the direction of movement. They suggested using a joystick to control navigation in the virtual world.

An interesting result from this experiment was the time spent by the participants on the 2D map. The eye tracking data shows us that the group that used the arrow cue (perceived by us as the easiest) exploited the 2D map to its fullest by spending most of their time looking at the 2D map. The other groups spent relatively less time on the 2D map as they had to compare what they saw in the 3D maze with what they understood from the 2D map. It is interesting to note that the strategy adopted by the group given the directional cue led them to the center of the maze much faster without needing to use the 3D environment as much as the other groups.

The low number of eye movement crossings for the arrow group indicates that the subjects were less confused about their orientation or location and hence jumped less often between the 3D maze and the 2D map. As expected, participants who received the arrow cue had a much better idea of where they were and which direction they were looking and hence had less doubt during wayfinding.

5. Future work

More research is needed to determine other factors that affect navigational behavior in VR. One of the limitations of this study is the size and gender distribution of the population. A larger group size would provide a stronger foundation for the results and inferences made. Further, because the gender distribution across the three different groups is not uniform (see Section 2), more work should be done to examine gender effects.

It is also important to measure the style of visual cue presentation. More work could be carried out regarding the manner the 2D map is displayed to the user. As shown by Darken et al. [DC99], the orientation of the 2D map is important to wayfinding. Use of an egocentric reference frame (ERF) versus a world reference frame (WRF), and the use of transparent overlaid maps, similar to what is found in computer games such as DOOM and Diablo, are also worthy of examination.

Use of cues in environments other than the maze (e.g., gaming, unmanned aerial vehicles (UAVs), and air traffic control) would allow for further understanding of how humans perform in real world environments. One of the limitations of the virtual maze is that it is strictly a search task. Increasing the complexity of the task by increasing the amount of interaction between the subjects and the VE would likely yield interesting results. It would also be interesting to explore how users employ their real world strategies in these conditions and if they are successful in doing so. This research is needed to gain a better understanding of wayfinding strategies employed by users. Such work could lead to the formulation of design guidelines helpful towards construction of more effective Virtual Environments.

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