Women Go With the (Optical) Flow

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ABSTRACT

Previous research reported interesting gender effects involving specific benefits for females navigating with wider fields of view on large displays. However, it was not clear what was driving the 3D navigation performance gains, and whether or not the effect was more tightly coupled to gender or to spatial abilities. The study we report in this paper replicates and extends previous work, demonstrating that the gender-specific navigation benefits come from the presence of optical flow cues, which are better afforded by wider fields of view on large displays. The study also indicates that the effect may indeed be tied to gender, as opposed to spatial abilities. Together, the findings provide a significant contribution to the HCI community, as we provide strong recommendations for the design and presentation of 3D environments, backed by empirical data. Additionally, these recommendations reliably benefit females, without an accompanying detriment to male navigation performance.

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INTRODUCTION

Published reports suggest that males significantly outperform females in navigating both real and 3D virtual environments (VEs). In a recent series of work [10,32], researchers explored the factors that contribute to this gender difference as well as proposed principles for designing systems to aid effective navigation. They demonstrated that, although large displays coupled with wide fields of view improved performance in the overall population, such systems are especially beneficial for females navigating in VEs. However, this research did not fully explain the specific factors that contributed to this effect, nor did it explicitly test to see whether the effect was more tightly coupled to gender or to spatial ability.

Figure 1. User working on experimental Dsharp display.

Gibson [15,16] showed that translation of an observer through an environment produces a radial pattern of optical flow at the eye. The fixed point in the flow field specifies the observer's direction of self-motion. Humans rely on these continuous visual cues for navigation in the real world. To assess the effects of optical flow in navigation through VEs, we used a spatial memory task in which participants first learned their way through a complex environment and were then tested for their memory of the route to the target location. Using this paradigm, we replicate and extend previous findings [10], demonstrating that observed benefits come from the presence of optical flow cues during navigation, cues better afforded by wider fields of view on large displays (Figure 1). Additionally, we show that the effect is tied to gender and not necessarily spatial ability.

The contribution of these findings is twofold. First, we provide a better understanding of previous results showing optical flow cues as responsible for benefits from wide fields of view on large displays. Second, we augment existing design principles for improving performance, especially for females, in virtual 3D navigation tasks.

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RELATED WORK

There exists a large body of work on general principles of 3D wayfinding and navigation. For example, Thorndyke & Hayes-Roth [33] have studied the differences between spatial knowledge acquired from maps and exploration. They define several forms of navigational knowledge: landmark knowledge, or orientation using highly salient landmarks; route knowledge, or navigation from one landmark to the next; and survey knowledge, or navigation using broader bearings and a cognitive map of the environment. When people learn new environments, they encode the information using one or more of these strategies. These principles have also been extensively studied in virtual environments [5,10,11,28,32]. The research exploring wayfinding has perhaps been a specific instance of interest in more general spatial problem solving and decision making principles [25]. As an example of the latter, Hunt & Waller [18] provide a review of research on orientation and wayfinding. They summarize work exploring the contribution of various artifacts such as maps as well as different strategies that people use to acquire spatial information. Additionally, they discuss individual differences, such as age and gender, which are related to spatial abilities in navigation effectiveness.

Gender and Spatial Ability

There exist summaries of the known gender differences in spatial abilities and navigation strategies [17,19,27,31], with most reports documenting male advantages in spatial tasks. In fact, authors such as Kimura [19] have argued that some of these differences may be biologically based. Several individual experiments [6,22] have explored these gender differences in various situations and present results that support these hypotheses.

For example, Voyer et al. [34] provide a meta-analysis on the magnitude and consistency of cognitive gender differences using a variety of spatial ability measures. Interestingly, they found partial support for the notion that the magnitude of gender differences has decreased in recent years. Devlin & Bernstein [12] tested how males and females utilized different kinds of wayfinding information. Their results indicated that males made significantly fewer errors and were significantly more confident in finding their way around in a computer simulated campus tour. They also concluded that males preferred the use of visual-spatial cues more than did females.

Cutmore et al. [8] performed a series of experiments examining the influence of gender, passive versus active navigation, cognitive style, optical flow, and brain hemisphere activation on the acquisition of route and survey knowledge in a 3D virtual environment using maze traversal tasks. The authors demonstrated significant gender differences in initial studies on navigation strategies and performance, and hypothesized that optical flow cues might have been driving the results. In a final experiment, they focused on the hypothesis that spatial ability, not gender, was driving the effectiveness of optical flow cues. However, to maintain a homogeneous population while exploring this issue, they included only female participants in their sample. Thus, although they did find that optical flow significantly benefited low spatial ability female users in navigating their 3D virtual environment, they could not report the specific influence of gender on these cues. In fact, we have found no reports in the literature suggesting that optical flow cues are more or less helpful based on gender.

Gender and Field of View

Recently, Czerwinski et al. [10] have shown that female 3D navigation performance can be enhanced and that gender differences may be significantly reduced with larger fields of view. In their paper, the authors also provide a review of prior work done exploring effects of field of view on performance of various tasks, presenting evidence that increasing field of view leads to perceptual, visual, and motor improvements in various navigation performance tasks [1,26]. Overall, wider fields of view are desirable for a wide variety of spatial tasks.

Optical Flow in Navigation

Gibson initiated a new field of study called ecological optics [15,16]. According to his theory, the pattern of light falling on the retina changes constantly as we move around in the environment, thus producing an optic flow field in the optical array. This optical flow, coupled with our proprioceptive and kinesthetic perception of motion, allows us to directly perceive the structure of the environment [13,21]. In Gibson's terms, we use the 'perceptive' structure of the changing visual scene to specify the 'invariant' structure of the layout of objects in the environment. Route knowledge, then, is perceived and learned according to a temporal sequence of changes in viewpoints within the invariant structure of the environment [35]. Warren et al. [37] provide an overview as well as various competing theories on how people derive their 'translational heading,' or movement through space, from the information available through vision. Bederson & Boltman show that optical flow provided by smooth animation improves people's ability to learn spatial positions and relationships of data [4].

It should be noted that optical flow is the relative motion of stationary objects around a moving observer. Eye movements are ignored in optical flow. These eye movements generate much more complex, swirling patterns of motion, called retinal flow, which are painted on the back of the eye [9]. Since users are largely physically stationary in our systems (e.g. they are not bouncing while navigating in 3D), we project our model of the flow field onto a spherical surface around the observer rather than relative to their fovea. Hence we consider only optical flow in our experiments, and assert that our findings are directly relevant to the design of 3D virtual environments, in which users are physically stationary as they navigate.

Loomis et al. [23] described path integration, the process of navigation by which the traveler's movement is updated to provide a current estimate of position and orientation within a larger spatial framework or cognitive map. However, because they did not differentiate between discrete and continuous movement, they did not explore the effects of optical flow on the acquisition of survey knowledge. In fact, in a separate paper, Klatzky et al. raised doubts about the benefits of optical flow in spatial learning in the absence of associated vestibular cues [21]. However, they were studying relatively simple single-movement responses, and we contend that optical flow, even in the absence of vestibular cues, may still be useful for navigating more complex paths. Kirschen et al. [20] examined the impact of optical flow on learning to navigate through synthetic environments. They found that in the absence of other cues, such as landmarks, optical flow cues were a significant aid in wayfinding. Users performed better learning a maze with fluid optical flow cues than with choppy ones. In our studies, we embrace the notion of path integration and explore in more detail how optical flow affects spatial learning in males and females.

Various researchers have claimed that, given optical flow, only the central visual field is necessary for accurate judgments of heading and velocity [3,7,36,37]. However, most of these studies relied mainly on standard computer displays with relatively small fields of view. They were interested mainly in showing that optical flow cues were not retinally invariant, or constant across the retina. They used discrete judgments without providing feedback to measure accuracy of perception of motion and did not document the utility of peripheral optical flow cues in navigation tasks. However, Richman et al. [29,30] used larger fields of view (up to 90 degrees) in virtual environments to provide optical flow in both active navigation and passive viewing. Their results suggest that optical flow in the periphery benefits heading perception, particularly during active navigation. We further explore this to determine if optical flow presented in various wider fields of view affects males and females differently during active navigation. Since previous studies [10] have shown benefits in relatively wide fields of view (75 degrees), we decided to explore how much we could expand fields of view before we stopped seeing incremental benefits.

EXPERIMENT

In our study, we extend previous investigations of the optimal field of view during 3D navigation tasks as well as examine the effects of optical flow cues.

Participants

Twenty-two volunteers (11 female) from the greater Puget Sound area were recruited from the Microsoft Usability database to participate in the study. Participants ranged from 13 to 50 years old. They were screened to be intermediate to expert Windows and Office users, as per validated internal screening tools, and none played more than 5 hours of 3D video games per week.

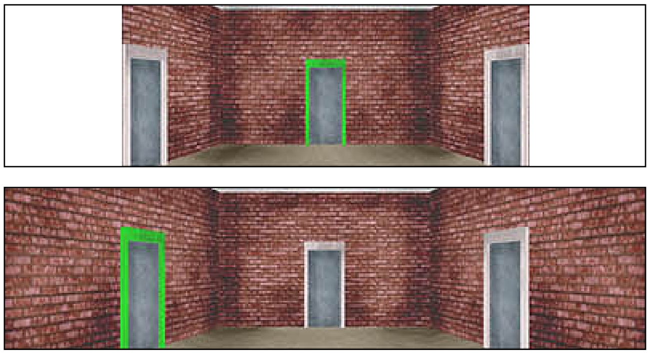

Figure 2. User views of the maze with narrow (above) and wide (below) fields of view. The user should follow the center door above and the left one below.

Tasks

We derived our tasks from Cutmore et al. [8], and designed them to examine not only the optimal field of view (FOV) for active navigation through a maze of 3D rooms, but also the absence or presence of optical flow cues while navigating. To that end, we used the Alice 3D authoring tool [2] to construct a DOOM-like maze. The user was positioned to start at an interior room position, and could then make simple turns (controlled by pressing the right, up, or left arrow keys) in order to find the exit from the maze. In each room, the user was always looking at 3 doors through which to travel (see Figure 2). Hence there were always exactly 3 turn options. Users could not go backwards through the maze. Each correct turn resulted in a door being raised and the user being moved to the middle of the next room.

When optical flow was present, the user saw animated movement of the virtual camera from the center of the current room through the door to the center of the next room. When optical flow was absent, the user simply saw the image fade out and a new one fade in as they were transported from the center of the current room to the center of the next room (no animated movement). For experimental validity, the time required for each move between rooms was kept constant at 2.5 seconds regardless of optical flow condition.

Each path through the maze involved a randomly selected path through 14 rooms. There were exactly 8 turns (left and right) and 6 straight movements in each path and paths were allowed to cross back over themselves. Several example paths through the maze are provided in Figure 3.

Because each room looked identical, the maze afforded few environmental cues, and learning routes through the maze required users to create some internal representation of the layout. There are several ways users could encode this path through the maze. First, users might encode their actions into a sequence, forming a symbolic representation of some kind. For example, a sequence may be of the form "up, left, right, left, up, left, left…", more easily "u, l, r, l, u, l, l…",

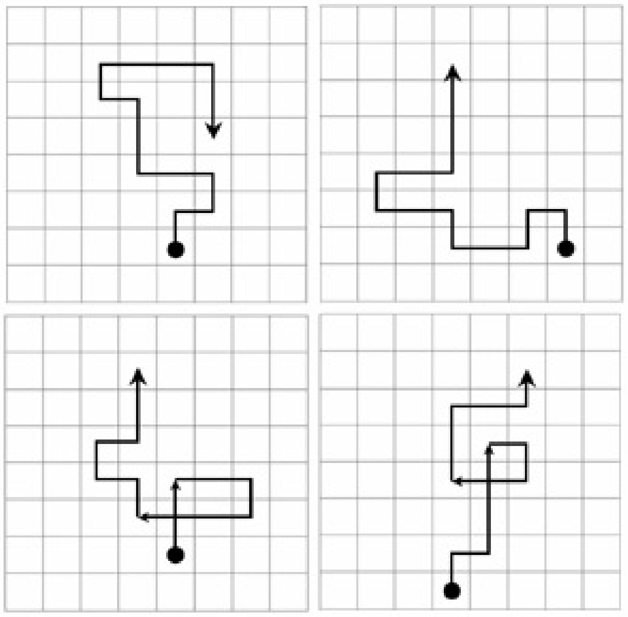

Figure 3. Example paths through the maze. Users never saw these overview maps.

or even mapping the directions to door numbers as "2, 1, 3, 1, 2, 1, 1…". Alternatively, users might generate a spatial representation of the environment, as we instructed them to do in this study. With this strategy, users would employ path integration to form a cognitive map of the environment. In order to encourage users to use the latter strategy, we implemented an additional test performed after each move. For each room, users were asked to determine if they had previously been in that room (i.e., if the path crossed itself). Only by building a cognitive map of the space could they accomplish this task.

Each participant completed five trials. The first trial was a practice trial, but was representative of the experimental trials. Each trial in the study consisted of three phases: learning, forward test, and backward test. During the learning phase of a trial, the user navigated through the maze while the computer displayed (via green highlighting of the door frame as shown in Figure 2) which turn (keypress) to take. If a user hit the wrong key, the incorrectly chosen door would flash red and the user would not move until the correct direction was chosen. During the forward and backward test phases, the green highlighting was removed and the user had to remember how to navigate the maze without the turn cues. Again, if the user attempted an incorrect turn, that door flashed red, after which the user could choose a different turn. A computer program kept track of the number of doors correctly and incorrectly opened, in addition to the time it took to complete the learning and two test phases of each trial. After each trial, the user provided a satisfaction rating for that set of optical flow and field of view settings on a scale of 1=frustrated to 5=satisfied. There was one trial for each combination of display settings: field of view (100 v. 120 degrees) x optical flow (absent v. present). After experiencing all of the display conditions, users were allowed to alter their satisfaction ratings to better reflect their overall preference for the display settings.

Prior to the start of the practice trial, users performed the VZ2 "paper folding" subtest, parts 1 and 2, from the Eckstrom et al. [14] Kit of Factor-Referenced Cognitive Tests. This test has been used to evaluate spatial ability skills and has been widely validated. Administration of the test with instructions took approximately 10-15 minutes. The entire session lasted approximately 1.5 hours and participants were compensated with a software gratuity for their involvement.

Equipment and Design

In our study, we used a novel, 43" wide surface, created by projecting 3 displays onto a curved plexiglass panel, each at a resolution of 1024 x 768, for an equivalent of a 3072 x 768 resolution display. We used Windows XP multiple monitor software to "stitch" the three desktops into one large, curved, display surface. The straight-line distance from left edge to right edge of the display area is 43 inches. The actual distance along the curve is 46.5 inches at the top and 47 inches at the bottom. The height of the display is 11 inches. The distance from eye to screen is 20 inches in the center, and 24 inches at the edges. The physical field of view for a user seated in this position is about 120 degrees. This display, which we call Dsharp, is shown in Figure 1.

We presented the virtual environments on the Dsharp display. The system maintained a frame rate of about 45 frames per second in all conditions. A Microsoft natural keyboard was utilized, although only the arrow keys and the spacebar were allowed for input.

The design of the study was a 2 (gender) x 2 (100 v. 120 FOV) x 2 (absence or presence of optical flow) x 2 (forward and backward tests) design. FOV and optical flow conditions were balanced using a Latin square design and the order of tests was fully counterbalanced. Dependent measures included spatial abilities scores, overall task times, number of doors opened correctly on first try, and user satisfaction ratings for each condition.

Results

Overall Manova. We submitted the data to a 2 (gender) x 2 (high v. low spatial ability) x 2 (forward v. backward direction) x 2 (100 v, 120 degree field of view) x 2 (optical flow cues present v. absent) repeated measures multivariate analysis of variance (RM-MANOVA). The first two variables were between subjects, the rest were within. The two dependent measures submitted to the analysis were task reaction time and the number of doors chosen correctly on the first attempt. Each dependent measure will be discussed separately in terms of main effects and interaction with other variables.

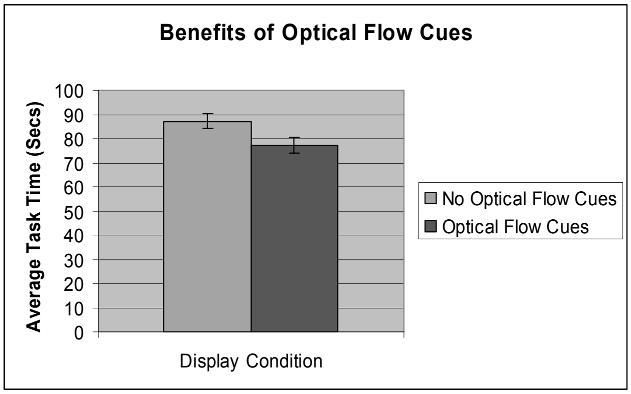

Figure 4. The presence of optical flow cues allows users to perform task more quickly.

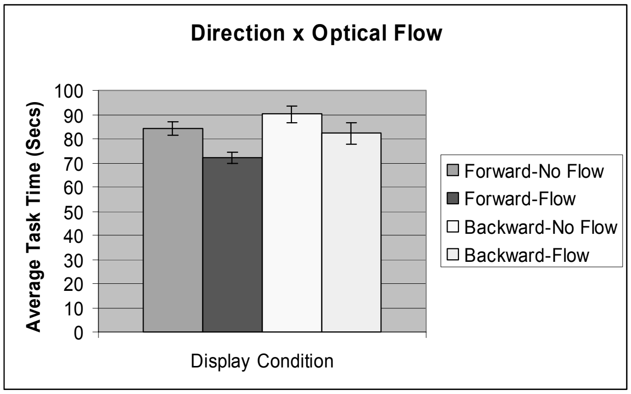

Figure 5. The presence of optical flow cues aids users more in the forward test.

Task Times. A main effect of direction was obtained for overall task time, F(1,18)=11.5, p=.003, with average task times in the forward test significantly faster than those in the backward test (forward=77.9 seconds, backward=85.8 seconds). In addition, as shown in Figure 4, there was a significant main effect observed for the optical flow factor, F(1,18)=15.22, p=.001. Having optical flow cues present during the 3D maze navigation task significantly shortened average maze traversal times (without optical flow=86.9 seconds, with optical flow=76.8 seconds). As shown in Figure 5, we found a borderline significant interaction between direction and optical flow, F(1,18)=12.6, p=.066, with optical flow benefiting users more in the forward direction. There was also a significant 3-way interaction between gender, optical flow, and direction, F(1,8)=12.63, p=.002. Follow-up post-hoc analyses revealed a significant gender x optical flow interaction in the forward, F(1,20)=8.20, p=.01, but not the backward direction. Females benefited significantly more from the optical flow cues, but only in the forward test. Perhaps the backward test was so difficult as to eliminate benefits observed in the forward test. This data is shown in Figures 6 and 7.

Number of Correct Doors Opened on First Attempt. A significant main effect of direction was observed for the number of correct doors opened on the first attempt, F(1,18)=11.5, p=.003, with the forward direction resulting in more correct turn choices, on average (forward=8.6, backward=7.5). No other main effects or interactions were significant at the p=.05 level for this dependant measure.

Spatial Abilities. As mentioned earlier, all participants were given the paper folding test to assess their spatial abilities. A split-mean division of the data was carried out, so that any score higher than 11.8 (the average score for these participants) was labeled as “high”, and any score below was labeled “low”. No main effects or interactions were observed for this measure. In other words, the males and females in our sample did not differ reliably on this metric. Males did score slightly higher than females, with a 12.0 v. 11.6 average, respectively.

User Satisfaction. A 2 (gender) x 2 (FOV) x 2 (optical flow) ANOVA was used to analyze the user satisfaction ratings for each display condition. A significant main effect of optical flow was obtained, F(1,20)=6.7, p=.017, with conditions incorporating optical flow cues rated as more satisfactory by users, on average. In addition, a significant interaction between gender and optical flow was observed, F(1,20)=5.6, p=.025, with females rating conditions with optical flow significantly more highly than males did, relative to no flow conditions.

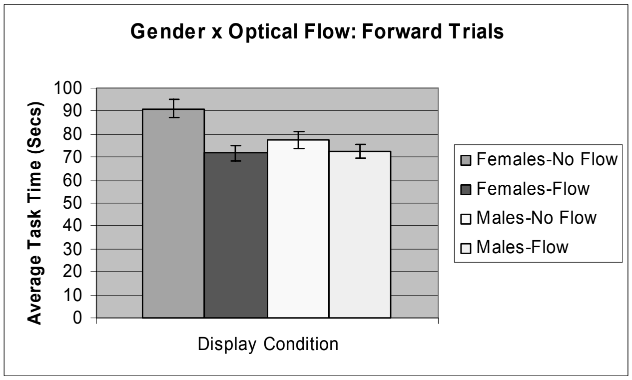

Figure 6. Optical flow cues benefit females significantly more in the forward test.

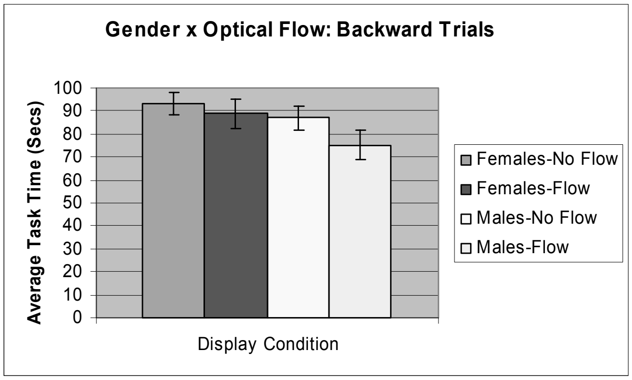

Figure 7. Optical flow cues benefit all users equally in the backward test.

DISCUSSION

Users were able to more quickly and more accurately recall paths going in the forward direction than going backward. This can be explained by the fact that regardless of encoding strategy, navigating backwards required users to perform an extra cognitive step in reversing the path. This added cognitive load may account for the slower and less accurate performance on the backward test.

Although there was no significant effect of optical flow on number of correct doors opened on first attempt, users were able to recall mazes significantly faster with optical flow present. After piloting the study, we picked the number of rooms (fourteen) and turns (eight) to tax working and long term memory. From debriefings with the participants, we believe that given a particular strategy, users performed as well as they were able. Reaction time in recall is therefore a good indicator of how well the spatial information was encoded and retrieved during the test phases.

One of the reasons we provided a forward and a backward test was to distinguish between users who encoded the paths sequentially as opposed to spatially. We expected that the former group would have more trouble flipping the path backward than the latter. As an analogy, most people can articulate the alphabet from A to Z effortlessly, but find it extremely difficult to recite it from Z to A. This is, presumably, because the alphabet is stored in a unidirectional fashion [8]. On the other hand, users that utilize a spatial encoding and form a cognitive map of the environment may have an advantage in backward navigation because only one mental rotation is involved [24]. We did not, however, observe this effect. It should be noted that although users may dominantly use one or the other, these encoding schemes are not mutually exclusive.

This being said, we would expect that the presence of optical flow would help users strengthen their spatial encoding of the paths. This hypothesis is supported in the result that optical flow helps females more than males in the forward test, since females have traditionally been described as "landmark" navigators, at least initially. User satisfaction ratings support these performance results in that all users significantly preferred having optical flow cues present, and females rated them significantly more satisfying than did males. In addition, since the paper-folding test revealed no significant differences in spatial ability between our gender samples, we assert that the effects reported here may be attributed to gender and not necessarily spatial ability.

Previous studies [10,32] demonstrated a performance advantage for larger fields of view. In our current study, we were hoping to learn more about the limits on increasing fields of view. The fact that there was no reliable performance difference between the 100 degree and 120 degree conditions indicates that there is no advantage to increasing field of view beyond 100 degrees for the particular class of navigation tasks we examined. We are currently also examining the effects of different fields of view for standard desktop productivity tasks to see if this new finding generalizes to other task domains.

CONCLUSION

This study demonstrated that there is a significant performance advantage for users navigating through 3D environments when optical flow cues are present. In addition, we have made a significant contribution to the field of HCI by demonstrating that this performance advantage is reliably larger for females than it is for males, and that this effect is not attributable to a gender bias in spatial abilities, at least in our sample population. This seems to be one of those rare findings in HCI where we have the opportunity to formulate design recommendations that benefit a large segment of the population without harming the rest of the users. A final contribution of this paper is that we explored very wide fields of view, much wider than many others doing research in this area, and have shown that a 100 degree field of view may be sufficient for many egocentric navigation tasks.

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