Re-evaluating Benefits of Body-based Rotational Cues for Maintaining Orientation in Virtual Environments: Men Benefit from Real Rotations, Women Don't.

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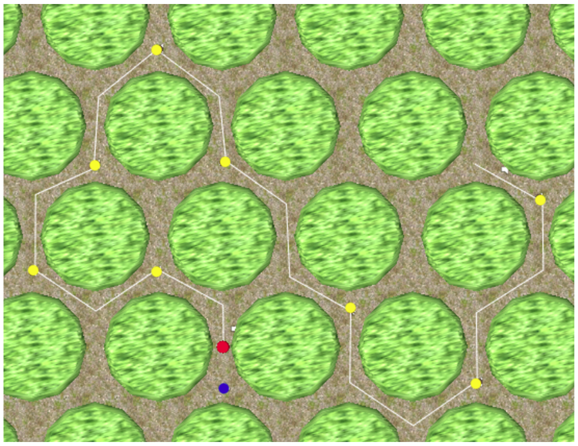

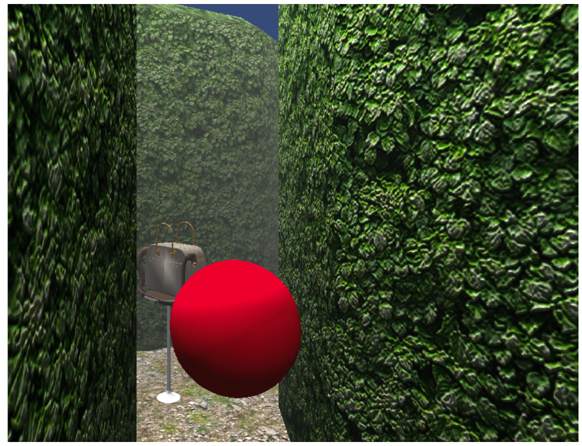

Figure 1: (Left) *One of the two variations of the virtual maze layout explored by participants. The second variation was a left-right mirror image of the first layout to ensure equal path complexity. Yellow dots represent locations of target objects. Dark-blue dot represents initial position of the participant. Red dot represents initial position of the guiding sphere.* (Right) *A screenshot of the virtual maze showing the red guiding sphere in the foreground and one of the target objects in the background.*

Abstract

Relying exclusively on visual information to maintain orientation while traveling in virtual environments is challenging. However, it is currently unclear how much body-based information is required to produce a significant improvement in navigation performance. In our study participants explored unfamiliar virtual mazes using visual-only and physical rotations. Participants's ability to remain oriented was measured using a novel pointing task. While men consistently benefitted from using physical rotations versus visual-only rotations (lower absolute pointing errors, configuration errors, and absolute ego-orientation errors), women did not. We discuss design implications for locomotion interfaces in virtual environments. Our findings also suggest that investigating individual differences may help to resolve apparent conflicts in the literature regarding potential benefits of physical rotational cues for effective spatial orientation.

CR Categories: H.1.2 [Models and Principles]: User/Machine Systems—Human factors H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities H.5.2 [Information Interfaces and Presentation]: User Interfaces—Input devices and strategies J.4 [Social and Behavioral Sciences]: Psychology

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1 Introduction

Maintaining spatial orientation is essential for navigation. A significant body of literature (see Ruddle [2013] for a recent review) demonstrates that the availability of body-based information during locomotion in virtual environments (i.e. using physical walking) enables better sense of direction and facilitates acquisition of spatial information compared to relying exclusively on visual information. Unfortunately, high equipment costs and physical space constraints render physical walking unsuitable for many practical applications. For these situations it may be useful to provide partial body-based information such as the ability to physically rotate during locomotion while remaining in place. However, relative efficiency of locomotion with rotational body-based information versus visual-only locomotion remains an open issue.

Triangle completion studies [Avraamides et al. 2004] demonstrate that availability of rotational body-based information can significantly improve one's ability to accurately update self-orientation during locomotion. One might expect that physical rotations should also help to improve performance in more complex navigation

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tasks. In fact, Riecke et al. [2010] found that using full-body rotations can lead to performance improvement in a navigational search task compared to visual-only rotations. This latter finding, however, seems to contradict a number of other studies, where availability of physical rotations did not result in significant performance gains over visual-only locomotion [Ruddle and Lessels 2009; Ruddle et al. 2011; Suma et al. 2010].

Performance in navigation tasks can be significantly impacted by individual differences between participants. Gender in particular affects navigation performance through its strong association with spatial abilities and proficiency with computer interfaces [Waller 2000]. Gender was shown to significantly affect spatial knowledge acquisition in both real and virtual environments (see Tlauka et al. [2005] for an overview). However, it is rarely explicitly considered as a factor in studies related to effects of body-based information in navigation tasks.

In this paper we present preliminary results from a study designed to revisit the role of physical rotation in facilitating navigation and remaining oriented while traveling in virtual environments. This study was designed to remedy some of the issues with the earlier attempts to explore the problem. First, instead of testing spatial knowledge of a fully-explored environment post-factum, we periodically gauged participants' sense of direction relative to previously visited locations while they were exploring an unfamiliar environment. Second, in contrast to studies by Ruddle et al. [2009; 2011], the same display was used for both visual-only and physical rotation interfaces. Third, the availability of rotational body information should primarily benefit participants by facilitating spatial updating strategy. Consequently, the virtual environment was designed to avoid spaces with distinct geometric shapes and 90° turns, which could facilitate navigation strategies other than spatial updating [Kelly et al. 2008]. Finally, we explicitly account for effects of gender on participants' performance.

2 Method

2.1 Environment

The virtual environment was designed as a hexagonal garden maze created by a regular grid of bushes (vertical pseudo-cylinders) arranged in such a way, that the centers of any three neighboring cylinders formed an equilateral triangle (Figure 1). This hexagonal structure meant that participants had to take left or right 60° turns at regular intervals. The relative sizes of the cylinders and the passages between them were selected to ensure that the lines of sight were blocked, i.e., a participant looking down a passage would never see beyond neighboring cylinders. The environment contained no global landmarks or other obvious directional cues.

We guided participants through the maze by asking them to follow a red sphere, which floated above ground along a pre-defined path. Invisible barriers prevented participants from straying too far from the path and getting lost. Eight distinct target objects (local landmarks) were randomly placed at certain locations along the path, as indicated in Figure 1. The placement order was randomized for each participant and each trial. At the beginning of the path participants generally encountered a new landmark every second turn; later on the landmarks were more sparse.

2.2 Experimental design and apparatus

The experiment used a within-subject design with two experimental conditions, defined by the available type of locomotion interface:

1. *Visual-only rotation* interface used joystick for rotation and translation. Participants were seated on a four-legged chair, which did not rotate.
2. *Physical rotation* interface used joystick for translation, but participants had to physically rotate on a swivel chair.

In both cases participants were wearing the same Oculus Rift Developer Kit head-mounted display (HMD), which provided 110° diagonal (90° horizontal) field-of-view with resolution at 1280 by 800 pixels shared between two eyes. Built-in head orientation tracking was enabled in both conditions to minimize motion sickness.

Participants used a wireless joystick to control their movement. Whenever participants encountered a new target object they were asked to stop and point (using the same joystick) to all previously seen objects (in random order). This allowed us to test how participants' orientation in the maze evolved over time as task difficulty gradually increased.

During the experiment participants sequentially explored two versions of the same environment, which were mirror images of each other. The order of presentation for the two virtual environments and the two interfaces was balanced across four groups of participants. After traveling through the first environment, participants removed HMD and headphones and took a brief break while the experimenter swapped the chair and prepared for the second trial with a different locomotion interface.

To ensure that participants were sufficiently familiar with the controls, each trial started with a brief practice. Participants travelled along a short path in a similar maze environment, encountered two target objects, and completed practice pointing tasks as described above.

2.3 Measures

Participants' spatial orientation performance was quantified using three complementary pointing measures:

Mean absolute pointing error - arithmetic mean of absolute pointing errors for all targets at a given location. Measures overall accuracy of the participants.

Absolute ego-orientation error - absolute value for the circular mean (see Batschelet [1981], pp. 7–15) of the signed pointing errors for a given location. Measures systematic bias in pointing errors, which can serve as an estimate of the error in participant's perceived self orientation.

Configuration error - mean angular deviation (see Batschelet [1981], pp. 33–37) of the signed errors for given location. Measures variability of pointing estimates and serves as a estimate of consistency for relative directions to multiple target objects.

2.4 Participants

Nineteen undergraduate university students (8 female, 11 male) volunteered to participate in this study and received course credit as compensation. Participants were approximately equally distributed across four possible combinations of presentation orders for two locomotion interfaces and two variants of the virtual maze.

3 Results

In our virtual environment devoid of obvious directional cues participants had to rely on path integration strategy to remain spatially oriented. Over longer stretches of the path participants would likely

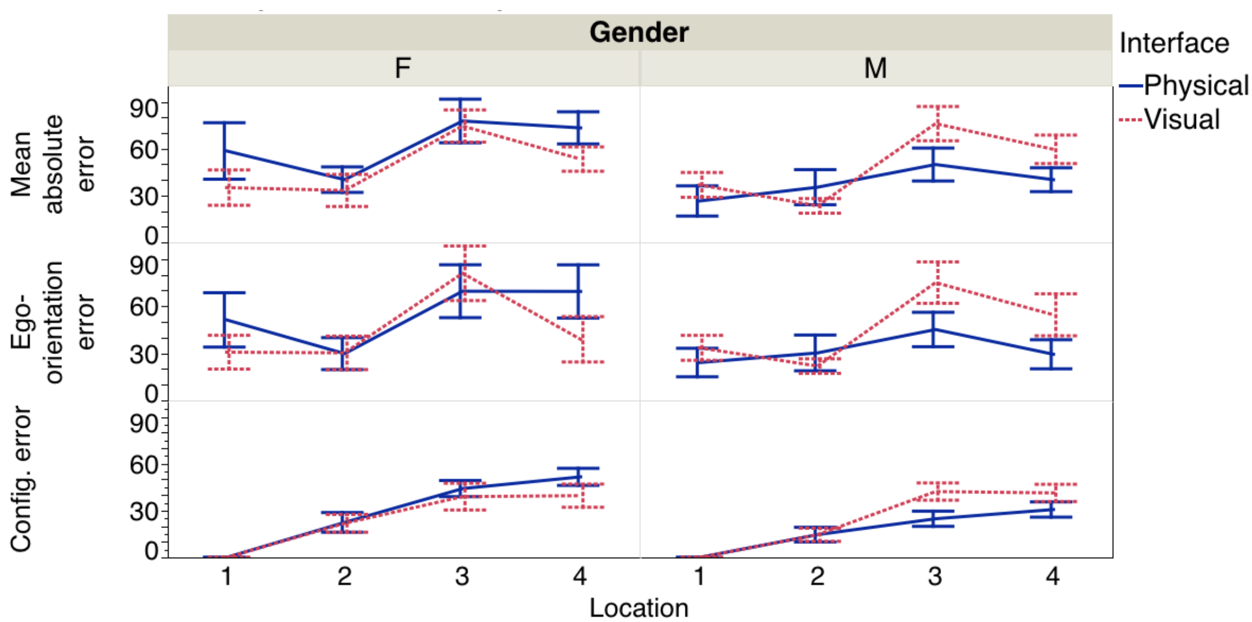

Figure 2: *Mean absolute pointing error (top), absolute ego-orientation error (center), and configuration error (bottom) in degrees as a function of location. Error bars represent standard errors. Note that configuration error at location 1 is by definition equal to zero because participants pointed only to a single target (start location).*

become disoriented due to inevitable accumulation of path integration errors, thus negating any potential differences between the two locomotion interfaces. During post-experiment interviews participants generally reported that the task was, in fact, extremely difficult and that they felt disoriented after visiting approximately four locations. Therefore, for this initial exploration of the data we decided to focus our attention on participants' performance at the first four locations.

For each of the three accuracy measures (mean absolute pointing error, absolute ego-orientation error, and configuration error) we constructed a mixed-effects statistical model that explored the relationship between a given accuracy measure as dependent variable and a full factorial combination of interface type, gender, and location (treated as nominal factor) as independent variables. The correlation of the two measurements obtained from the same participant was modeled as a random effect of participant. Figure 2 summarizes participants' performance at the first four locations.

Mean absolute pointing error showed a significant two-way interaction between Gender and Interface ($F(1, 115) = 7.7, p = .006, \eta^2 = 0.038$) and a significant main effect of Location ($F(3, 115) = 14.88, p < .001, \eta^2 = 0.187$), predictably suggesting that absolute errors differed with pointing location. The remaining effects were not statistically significant. To explore the interaction between Gender and Interface further we conducted planned comparisons. The results are summarized in Figure 3 (left). For male participants we found a trend towards lower absolute errors when using physical rotations as compared to the visual-only locomotion interface ($t(115) = 1.84, p = .068$). In contrast, female participants exhibited significantly higher absolute errors for the physical rotation interface ($t(115) = -2.08, p = .04$).

For absolute ego-orientation error we similarly found a significant two-way interaction between Gender and Interface ($F(1, 119) = 4.88, p = .03, \eta^2 = 0.027$) and a significant main effect of Location ($F(3, 119) = 14.88, p < .001, \eta^2 = 0.151$). The remaining effects were not statistically significant. Planned comparisons revealed that male participants exhibited significantly lower ego-orientation errors when using the physical rotation interface ($t(119) = 2.01, p = .047$). There was no significant differences between the two interfaces for female participants ($t(119) = -1.2, p = .234$). The results are summarized in Figure 3 (center).

For configuration error we also found a significant two-way interaction between Gender and Interface ($F(1, 119) = 5.8, p = .018, \eta^2 = 0.038$) and a significant main effect of Location ($F(3, 119) = 63.33, p < .001, \eta^2 = 0.564$). The remaining effects were once again not statistically significant. The follow-up planned comparisons revealed that male participants exhibited significantly lower configuration errors when using the physical rotation interface ($t(119) = 2.27, p = .025$). There was no significant differences between the two interfaces for female participants ($t(119) = -1.23, p = .22$). The results are summarized in Figure 3 (right).

4 Discussion and conclusions

All three measures of participants' accuracy in pointing tasks are in agreement, indicating that men were able to take advantage of physical rotations to improve their absolute pointing accuracy, ego-orientation, and consistency of relative directional estimates for multiple pointing targets as compared to the visual-only interface. In contrast, while women perfumed similar to men when using visual-only interfaces, they failed to improve (and, in fact, showed deteriorated performance based on absolute pointing error measure) when using physical rotations.

These gender differences are somewhat surprising given that, to the best of our knowledge, no other studies investigating the effects of body-based information on performance in navigation tasks reported such differences. However, our results are consistent with findings that men are more likely to rely on spatial updating strategy in pointing tasks, whereas women tend to rely on landmark-based information [Lambery and Berthoz 2007]. Our virtual maze was designed to bias participants toward the former strategy, which may also have exposed underlying gender differences related to the

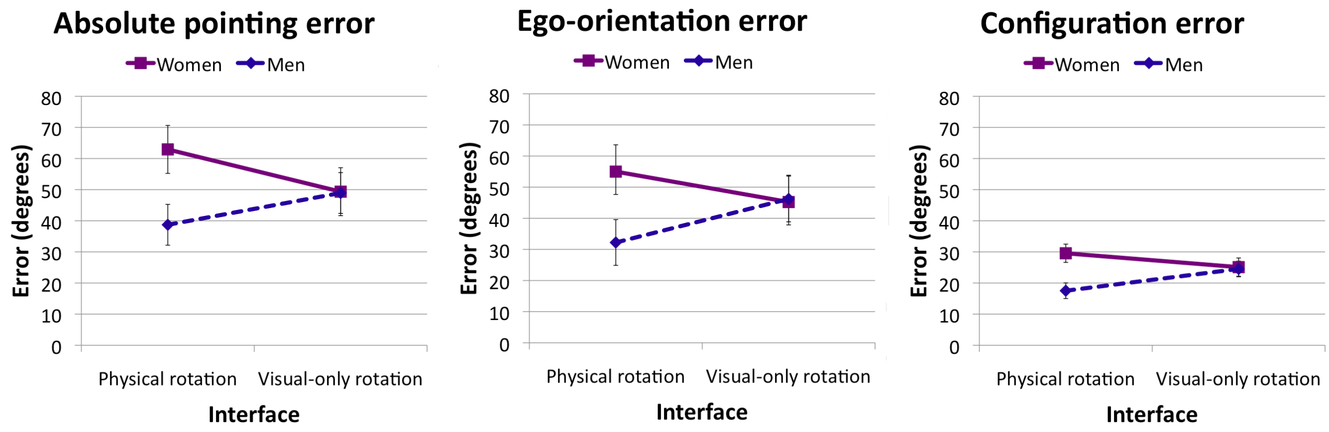

Figure 3: *Effects of gender and interface type on mean absolute pointing error (left), absolute ego-orientation error (center), and configuration error (right). Error bars represent standard errors.*

use of various navigation strategies.

Waller [2000] suggests that gender-related gaps in navigation performance may be better explained by underlying individual differences in cognitive spatial abilities co-related with gender. Significant individual differences may help to explain why previous studies where unable to detect benefits of physical rotation. Studies also show that the corresponding performance gap can be at least partially closed with additional practice [Lawton and Morrin 1999] or by making appropriate design choices for the interface [Czerwinski et al. 2002] to facilitate navigation performance for one group of users without negatively impact on the other group.

In order to develop design guidelines for the use of physical rotation in locomotion interfaces we plan to further explore gender related differences in navigation performance. In particular, we plan to correlate the differences in performance between visual-only and physical rotation interface with measures of individual spatial cognition abilities (such as psychological tests, self-reported experience with 3D gaming, and performance in real-world navigation tasks) to determine whether any of these measures may explain the differences better than a simple classification of participants by gender.

Acknowledgements

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