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Navigation in virtual environments using head-mounted displays: Allocentric vs. egocentric behaviors

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ABSTRACT

User behaviors while navigating virtual environments (VEs) using head-mounted displays (HMDs) were investigated. Particularly, spatial behaviors were observed and analyzed with respect to the virtual navigation preferences and performance. For this, two distinct navigation strategies applying allocentric and egocentric spatial perspectives were used. Participants utilized two different user interfaces (i.e., a multitouch screen and a gamepad) to employ the aforementioned strategies to perform a series of rotation, surge motion, and navigation tasks. Two allocentric and two egocentric metaphors for motion techniques—digital map, canoe paddle, steering wheel, and wheelchair—were established. User preferences for these motion techniques across the tasks were then observed, and their task performances on the two given interfaces were compared. Results showed that the participants preferred to apply egocentric techniques to orient and move within the environment. The results also demonstrated that the participants performed faster and were less prone to errors while using a gamepad, which manifests egocentric navigation. Results from workload measurements with the NASA-TLX and a brain-computer interface showed the gamepad to be superior to the multitouch screen. The relationships among spatial behaviors (i.e., allocentric and egocentric behaviors), gender, video gaming experience, and user interfaces in virtual navigation were also examined. It was found that female participants tended to navigate the VE allocentrically, while male participants were likely to navigate the VE egocentrically, especially while using a non-natural user interface such as the gamepad.

1. Introduction

Virtual environments (VEs), also known as virtual reality (VR), have gained much popularity and been employed in various applications. Many of these applications allow users to travel in the environment. Applications such as touring applications, 3D adventure games, and teleoperation systems employ specific user interfaces (UIs) to enable users to navigate their environments. For instance, a touring application such as Google Street View features click-to-go for transporting users virtually to any point within the view (Anguelov et al., 2010), and 3D adventure games and teleoperation systems utilize various user interfaces, such as a mouse, keyboard, joystick, or gamepad, for virtual navigation. It is also possible to leverage head motion as a user interface in head-mounted display (HMD) teleoperation systems (Martins & Ventura, 2009).

The combination of VE with HMDs has developed over the last two decades. Myriad industries have been adopting VE technology with HMDs for their needs (Berg & Vance, 2017), and HMDs are being manufactured and distributed to consumers at affordable costs. This technology is likely to be ready for mass-market adoption soon. This adoption will require further studies on cognitive psychology, particularly regarding the presentation of an intuitive user interface for VE navigation that can also benefit users' spatial cognition.

1.1. Aims of study

A previous study modeled a concept of a traveler holding a paper map as a metaphor for VE navigation (Fabroyir, Teng, Wang, & Tara, 2013, 2014). The concept adopted a proposal by former research (Darken & Cevik, 1999; Pausch, Burnette, Brockway, & Weiblen, 1995), except that it was in a non-HMD VE system and physically on two separate views. One of the views was displayed on a multitouch screen, and the other one was presented on a curved monitor. In addition, the system supplied a user interface

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overlaid on the multitouch map view to assist the physical navigation element.

In the previous study, the user interface was a control variable. The users could only apply the motion techniques that had been specified. Hence, it seemed worthwhile to reproduce the research as a pilot experiment to see how the users would behave in VE navigation if the techniques were not specified. In the experiment, the users were instructed to perform any gestures on the multitouch screen to move forward in the VE. Surprisingly, some of them used two fingers, swiping in opposite directions on the screen. This gesture behavior represented the users leveraging their allocentric perspective to shift the map view backward in order to move the VE viewpoint forward. Nevertheless, when the users were instructed to perform rotation in the VE, they executed either the steering motion gestures or typical rotation gestures on the multitouch screen.

The phenomenon observed during the pilot experiment suggested a need for a deeper investigation into users' spatial behaviors, especially in HMD VE navigation. Unlike a desktop, curved, or large projection screen, an HMD occupies the entire visual field of the user; thus, it appeared important to determine whether their allocentric perspective would dominate when there was no way for the users to perceive the physical map view visually.

Along with the existing multitouch screen in the previous study, a gamepad was added as an alternative interface. In contrast to the multitouch screen, the gamepad is commonly used as an egocentric navigation interface for controlling the movement of avatars in virtual environments. The aim of this addition was to observe users' spatial behavior preferences and navigation performance on these disparate user interfaces. In particular, no motion controllers were incorporated in the current study so as to present the metaphor of holding a paper map from real-world navigation. While holding the map, the gaps between users' hands are static. Accordingly, motion controllers would break this metaphor.

In summary, the research question of this study was “How do users behave and perform while navigating VEs on HMDs?” This question was further detailed as follows.

(a) Do users behave more allocentrically or egocentrically while navigating VEs on HMDs?
(b) How does user performance in VE navigation across spatial behaviors? Which spatial behavior does result in better performance in terms of time, error, and workload?
(c) Does spatial behavior correlate with users' gender, video gaming experience, and attitude towards the user interfaces (e.g., multitouch screen, gamepad)?

1.2. Allocentric vs. egocentric navigation

Basically, navigation is a combination of mental (i.e., wayfinding) and physical (i.e., motion) elements (Darken & Peterson, 2014, ch. 19). Both elements should be viewed thoughtfully in the construction of a user interface for VE navigation. Furthermore, this construction should consider spatial representation, namely allocentric and egocentric representations as shown in Fig. 1. Thus, users may leverage the interface to improve their navigation performance and spatial cognition.

To illustrate, mapping applications used in the aforementioned pilot experiment leveraged allocentric spatial representation for navigation. The pilot participants navigated the applications by incorporating object-to-object perspective transformation (see Fig. 1a) such as map panning, zooming, and rotation (Klatzky, 1998; Kozhevnikov, Motes, Rasch, & Blajenkova, 2006; Münzer & Zadeh, 2016).

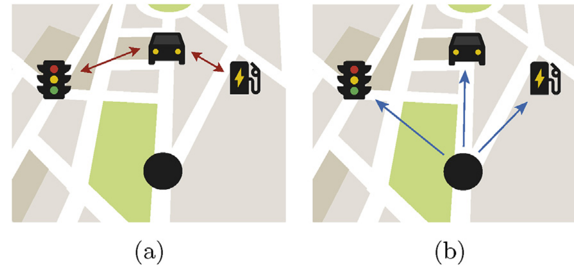

Fig. 1. Spatial representation in navigation: (a) allocentric navigation locates objects with respect to other objects (i.e., object-to-object), (b) egocentric navigation locates objects relative to the self (i.e., self-to-object).

In addition, the applications also supported egocentric representation for navigation. Fig. 1b illustrates how egocentric representation leverages self-to-object spatial coding to perform navigation. In fact, the interface in the pilot experiment allowed the users to mimic steering motion gestures, reflecting the egocentric behavior of a car's driver (Fabroyir et al., 2013).

1.3. Related work

The way people navigate the real world is applicable to VEs. There are several design principles for VE navigation based on cognitive psychology and environmental methodologies (Darken & Sibert, 1996). One of the principles is the presence of a virtual map. For users to navigate the VE effectively, the map orientation should be congruent with the environment, which is perpendicular to the floor and not in a vertical position. According to the real-world metaphor, this principle mimics travelers holding paper maps in the front of their body (Fabroyir et al., 2014).

On top of that, the virtual map should always show a viewpoint or a you-are-here (YAH) marker whose position changes dynamically across the map. Thus, as users travel through the VE, this viewpoint minimizes the positional transformation between egocentric and allocentric frames of reference (Darken & Cevik, 1999). In fact, users need to perform mental rotations to align these two frames continuously during navigation for map localization. However, the operation cost is minimum as long as the map and the viewpoint are in a track-up arrangement (Aretz & Wickens, 1992).

Mental rotation is important for establishing navigation awareness. The performance of mental rotation and navigation relies on the individual's spatial ability, which varies from one user to another. Some studies have examined whether this performance is gender-specific. The findings of those studies have favored males over females (Castelli, Latini Corazzini, & Geminiani, 2008; Lawton, 1994; Lawton et al., 2010; Saucier et al., 2002). This performance difference across gender, which emerges at early ages (Merrill, Yang, Roskos, & Steele, 2016), influences users' strategies for navigating VE. Users with good spatial ability encode landmarks and routes to build a mental representation of the VE directly, whereas users who lack this ability have to depend on verbal strategies (Wen, Ishikawa, & Sato, 2013).

Previous researchers developed systems to examine navigation strategies in VEs. Some of the studies set up the systems on desktop displays. Altogether, they made a number of findings. First, the mouse was the best one-handed interface for navigating the desktop VE (Lapointe, Savard, & Vinson, 2011). Second, more experience in gaming led to superior performance in virtual navigation (Murias, Kwok, Castillejo, Liu, & Iaria, 2016). Third, both egocentric and allocentric views of VE should be available for users as self-directed learning aids (Münzer & Zadeh, 2016). The first