Int. J. Human-Computer Studies 96 (2016) 1–11

Contents lists available at ScienceDirect

Int. J. Human-Computer Studies

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

Registration errors in beacon-based navigation guidance systems: Influences on path efficiency and user reliance

Tad T. Brunyé [a,b,c,*], Joseph M. Moran [a,b], Lindsay A. Houck [a,b], Holly A. Taylor [b,c], Caroline R. Mahoney [a,b]

[a] Cognitive Science Team, United States Army Natick Soldier Research, Development and Engineering Center, 15 Kansas St., Natick, MA 01760, USA
[b] Center for Applied Brain & Cognitive Sciences, 200 Boston Ave., Medford, MA 02155, USA
[c] Department of Psychology, Tufts University, 490 Boston Avenue, Medford, MA 02155, USA

ARTICLE INFO

Article history:
Received 8 January 2016
Received in revised form
6 June 2016
Accepted 18 July 2016
Available online 19 July 2016

Keywords:
Navigation
Augmented cognition
Trust in automation
Perception-action
Virtual environments

ABSTRACT

Emerging augmented reality displays provide high fidelity overlays onto real-world environments to enable navigation efficiency. The accuracy of these systems, however, is highly contingent on monitoring and registering user orientations and landmark locations. No data exist, however, regarding ranges at which registration error reliably influences user behavior and trust. The present experiments examined the influence of directional error in a simulated navigation guidance system on path efficiency and user trust. In three experiments, participants (N=90) navigated an urban desktop virtual environment with the assistance of an overlaid beacon depicting the direction and distance of a target landmark. Directional error was introduced into the beacon across trials, manipulated in 15° increments from 0° to 60° (Experiment 1), 5° increments from 0° to 20° (Experiment 2), and 1° increments from 6° to 10° (Experiment 3). Users show tolerance for up to approximately 8° angular direction error without significantly reducing path efficiency or user trust in system reliability. They also show reduced path efficiency emerging at lower angular errors (approximately 9°) relative to influences on perceived trust (approximately 16–20°). Results provide some basic heuristics for error tolerance, demonstrate important dissociations between the objective versus perceived impact of error in navigation displays, and contribute to theoretical positions regarding the optimization of global awareness and spatial knowledge acquisition.

Published by Elsevier Ltd.

1. Introduction

Augmented reality provides real-time enhancement of direct perception by overlaying virtual information onto the real world. Augmented reality systems are being adopted across multiple domains including medicine, navigation, advertising, and education, can take on fixed and mobile forms, and can convey an increasingly wide range of information types (Carmigniani et al., 2011). The promise of augmented reality is to enhance user performance by providing task-relevant information in real-time integrated into, and without shifting attention away from, the real world scene. The performance benefits that accrue from augmenting reality are becoming widely documented in the scientific literature, for instance in driving (Medenica et al., 2011), surgical training (Matu et al., 2014), and aviation (Foyle et al., 2005). The present research focused on navigation guidance as one particularly promising application of augmented reality. The notion is that by overlaying navigation information onto the visual world (e.g., onto an otherwise transparent lens), in the form of route guidance or a beacon, systems can optimize spatial awareness and increase navigation efficiency for drivers or pedestrians (Kim and Dey, 2009). To examine these issues, we simulated an augmented reality beacon in a desktop virtual environment, and measured its impact on user navigation and trust in system effectiveness.

While augmented reality has progressed tremendously over the past several decades, it also faces several technological challenges that limit system accuracy, reduce user performance, and reduce user trust in system reliability (Van Krevelen and Poelman, 2010). Broadly speaking, these limitations include: (1) the complexity of generating accurate 3D models and annotations of complex environments (Bartie et al., 2015; Behzadan and Kamat, 2007; Picard, 2003), (2) tracking a user's movement and orientation relative to the real-world (Azuma, 1997; Foxlin et al., 2015), and (3) registration between the virtual and real worlds, involving

* Corresponding author at: Center for Applied Brain & Cognitive Sciences, 200 Boston Ave., Medford, MA 02155, USA.
E-mail address: tbruny01@tufts.edu (T.T. Brunyé).

http://dx.doi.org/10.1016/j.ijhcs.2016.07.008
1071-5819/Published by Elsevier Ltd.

the relation between a user's current position and orientation, the 3D world model, and the visual display (Holloway, 1997; Tomioka et al., 2013). The present study focuses on the challenge of accurate registration between the virtual and real worlds. In a near-perfect system, such as with indoor Polhemus magnetic tracking, registration can proceed with relatively high accuracy and low latency. In contrast, outdoor environments where a user is free to walk and look wherever they please and tracking infrastructure is limited, pose a particular challenge for movement tracking and registration. For instance, magnetic compasses can vary widely ($+/-5°$) in accuracy due to variability in the Earth's magnetic field, and Global Positioning Systems (GPS) can produce dynamic orientation errors on the order of $+/-10°$ (Azuma, 1997). A recent study demonstrated that even a stationary gyroscope (in an iPad 3) demonstrates yaw drift of $+/-10°$ over the course of 12–18 h (Madsen and Stenholt, 2014). Of course, certain environments such as those characterized by tall buildings (i.e., *urban canyons*) or mountains, can result in even more severe positioning and relative direction errors (Duncan et al., 2013; Miura et al., 2015). As noted by Van Krevelen and Poelman (2010, pg. 6), “determining the orientation of a user is still a complex problem with no single best solution.”

For an ambulatory user relying on augmented reality to navigate between landmarks in a complex environment, registration errors may influence both navigation efficiency and the user's trust in system reliability. Registration error describes a condition under which virtual objects displayed on an augmented reality system appear in an incorrect position relative to the real world (Holloway, 1997). Error can be systematic as in a consistently biased signal, or relatively dynamic with a degree of randomness over time and as a person moves and reorients. Though it is clear that tracking difficulties are pervasive and vary widely with application, no research to date has investigated how registration error influences user experience during navigation. The present experiments examine how varying levels of systematic orientation error influence two primary aspects of user experience; first, we assess its quantitative influence on user efficiency navigating a large-scale virtual urban environment. Second, we assess its qualitative influence on users' trust in the system to efficiently guide them to a destination. Together, we provide more comprehensive understandings of how tracking and registration errors influence human behavior and perceptions of system utility. To motivate our research and develop hypotheses, we briefly review literature pertaining to augmented reality for navigation support, and system reliability influences on trust and user acceptance of novel systems.

1.1. Augmented reality for navigation support

Augmented reality offers opportunities to enhance ambulatory navigation efficiency by augmenting the perceived world with spatial information including distances and directions to destinations (Cankaya et al., 2015; Thomas et al., 1998; Yu et al., 2015). Much like an in-vehicle navigation support system, augmented reality systems for navigation can display varied information types (e.g., system status, direction, distance, time) across a multitude of formats and sensory modalities (visual, tactile, auditory). Visual augmented reality displays also vary widely in display principles, with some navigation systems depicting semi-transparent paths overlaid onto the real world, and others depicting a beacon indicating the direction of a destination (Cankaya et al., 2015; Fischer and Gellersen, 2010; Kim and Dey, 2009; Loomis et al., 1998; Narzt et al., 2005). The former is intended to provide turn-by-turn instructions to the user, also communicating the distance until the next turn; the latter is intended to convey a destination's direction and distance relative to the user's position, supporting basic locomotor guidance (Foo et al., 2005; Wiener et al., 2009).

The present study focuses on a beacon-based navigation system. Beacon-based systems do not provide turn-by-turn instructions. Rather, these systems require the user to actively engage in spatial decision making, such as where to turn and in which direction. From a technical and computational perspective, the central processing demands and updating latencies associated with the beacon system are lower given it does not require dynamically recalculating turn-by-turn direction sequences as a user strays from a path (Pielot and Boll, 2010). Practically speaking, the beacon system also occupies less screen real estate and thus may be less likely to occlude visual perception of the real world. Furthermore, because users need to actively engage in spatial decision making to reach their destination, a beacon-based aid may prove less detrimental to spatial memory development relative to turn-by-turn instructions (Bakdash et al., 2004; Chrastil and Warren, 2013). Thus, there are several potential advantages to using beacon-based navigation support systems, and augmented reality is a viable platform for conveying this information while allowing users to maintain direct perception of, and engagement with, the built and natural environment.

1.2. Perceptions of trust and system reliability

As first proposed by Muir (1987), trust is a critical moderator of the relationship between humans and machines, influencing system adoption, continued use, and user performance. Users can be spontaneously biased toward distrust in novel systems (Sheridan and Hennessy, 1984), and continued distrust results in users performing tasks without system support, leaving little to no opportunity for reevaluating and readopting the system (Muir, 1994). A strong predictor of user trust is the type and frequency of perceptible system faults; as faults increase, users will abandon a system if they believe it performs at a lower level than their own knowledge and ability (Chavaillaz et al., 2016; Lee and Moray, 1994). Though there are a number of competing theories explaining the development and disintegration of trust, there is general agreement that it is a useful construct for predicting and explaining real-world behavior and interactions with support systems (Cohen et al., 1998; Lee and See, 2004; Madhavan and Wiegmann, 2007; Parasuraman et al., 2008).

As with tagging landmarks for informational purposes (Van Krevelen and Poelman, 2010), beacons for localizing a landmark and providing distance information require accurate registration not only to support user navigation but also decrease perceptible system faults (Ha et al., 2012). There is some empirical evidence that perceptible registration error in landmark annotation can adversely impact users' trust in the reliability of augmented reality. Users explicitly note losing trust in augmented reality when landmarks are tagged with annotations that do not reliably register, in dynamic ways, with the directly perceived landmark (Vozar and Tilbury, 2012; Wither et al., 2011). For instance, users may lose trust when a beacon notes the location of the library, but is displaced by some degree of angular error from the library itself. It remains to be determined, however, the requisite angular error for users to both perceive and distrust a navigation aid. Distrust in augmented reality likely moderates the relationship between registration errors and long-term adoption of systems by users. Though no research to date has examined the possibility, parametric increases in registration error in navigation systems may decrease perceptions of trust; the present experiments examine this possibility, and identify error ranges that reliably produce user distrust in augmented reality navigation supports.