Registration Errors in Beacon-based Navigation Guidance Systems:
Influences on Path Efficiency and User Reliance

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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.

Keywords: navigation, augmented cognition, trust in automation, perception-action, virtual environments

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 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 ($\pm 5^\circ$) 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 $\pm 10^\circ$ (Azuma, 1997). A recent study demonstrated that even a stationary gyroscope (in an iPad 3) demonstrates yaw drift of $\pm 10^\circ$ over the course of 12-18 hours (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 (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.

1.3 The Present Experiments & Hypotheses

The present three experiments were aimed at testing the impact of navigation beacon registration errors on objective navigation performance and subjective trust in a navigation support system. Participants navigated a large-scale virtual environment with the support of a

simulated augmented reality navigation beacon indicating the direction and distance to a series of destinations. To simulate registration error, we parametrically varied systematic angular error between the destination and the depicted beacon. Across experiments, we successively approximated the directional error that reliably impacts users' navigation performance and trust.

Given the paucity of research in this specific domain, we made three relatively general hypotheses. First, we hypothesized that increasing directional error in beacons would negatively influence the objective efficiency with which navigators would select paths and navigate toward destinations. Second, we hypothesized that increasing directional error would decrease users' subjective trust in the system. Third, because self-report probing for perceived trust is subjective and may rely on conscious awareness of system limitations (Lee and See, 2004; Merritt et al., 2013), we hypothesized that impacts on navigation efficiency might emerge at lower angular errors than the subjective experience of distrust in system performance. In other words, the degrees of angular error for producing navigation efficiency costs may prove lower than the degrees of error for perceived distrust in the system (Manzey et al., 2012).

2. Experiment 1 Method

2.1 Participants

A total of 30 Tufts University students (14 male, 16 female, Mage = 20.1, 8 video game experts, 22 non-gamers) participated for monetary compensation (\$20USD). All testing procedures were approved by the institutional review board of Tufts University, with secondary approvals by the U.S. Army Human Research Protections Office.

2.2 Design

A within-participants repeated-measures design was used, involving exposing each participant to five directional error conditions (0°, 15°, 30°, 45°, and 60° angular error). The

dependent variables were navigation efficiency, which related participant produced virtual paths to optimal paths calculated using the A* path finding algorithm (Hart et al., 1968), and self-reported trust collected via an ordinal ratings scale. The study took approximately 30 minutes to complete.

2.3 Setting

The experiment took place in a climate-controlled indoor laboratory setting, with participants seated at a computer workstation equipped with a 24" display, keyboard, and mouse.

2.4 Virtual Reality Apparatus

We developed a custom urban virtual environment and a simulated augmented reality beacon. The virtual environment (Figure 1) was developed using the Unity 3D game development framework, containing a total of 553 buildings, 42 of which were labeled (e.g., *ZigZag Records*). Twenty-one of the labeled landmarks had facades that visually resembled each landmark's stated function (e.g., Laundromat, Pet Store), and were used as goal destinations during navigation. The overall environment was approximately square, 1.29 km² in size.

We simulated an augmented reality navigation beacon by creating a visual overlay on the upper center portion of the virtual environment. The beacon indicated the direction of the current destination goal and provided a real-time updated vector-based (straight line) distance to the destination (in meters). A view of the environment with the beacon overlay is depicted in Figure 2. The beacon would always indicate the direction of the destination (plus any introduced error), and thus changes in user orientation would move the beacon off-screen when outside of the field of view.

The game software automatically tracked and output user location over time, including environmental coordinates (x, y) and orientation (yaw). Data were output to a log file, which

sampled only when the user changed either coordinates or orientation. Maximum sampling frequency with continuous user movement was 60Hz.

2.5 Trust and Demographics Instruments

We developed a demographics instrument to probe for participant age, sex, video game experience (Boot et al., 2008), and spatial sense of direction (Hegarty et al., 2002). We also developed an instrument to probe for participants' extent of trust in the beacon following each navigation trial, using a numbered 1-7 scale anchored at 1(Not at all), 4(Moderately), and 7(Extremely). The demographics instrument was completed separately from the primary navigation task. The trust instrument was embedded in the navigation task, administered immediately upon reaching each goal destination, asking: *"How much did you trust the on-screen aid to guide you to this location?"*

2.6 Procedure

During an experimental session, following consent participants completed the questionnaires and then were guided through a practice session to familiarize themselves with the navigation controls. During practice, participants navigated in an open environment containing 6 labeled landmarks (e.g., cat, pool, chair) and were instructed to navigate between successive goals. The navigation beacon was available at all times and incorporated zero angular error. Upon arrival at a goal, the upper left of the screen would print "Congratulations on finding the [goal name]. Now locate and move toward the next target [goal name]." Practice was provided as an opportunity to learn the gaming controls (W-forward, mouse-look), and understand how to use the navigation beacon to guide movement between successive landmark goals.

Following practice, participants were placed in the primary urban environment and instructed to “find each destination as quickly as possible.” They were also given the following instructions: “an on-screen navigation aid will help you find your destination. However, the navigation aid might not always be perfect. For some destinations, you will be able to fully trust it to quickly guide you to the destination. For other destinations, you might find it somewhat inaccurate and taking you off course. After you reach each destination, we will ask you to rate (on a scale from 1 to 7) how much you trusted the navigation aid to get you there. If you think the aid was highly accurate and you trusted it, you should rate it highly. But if you did not trust the aid to keep you on the ideal route to the destination, you should rate it lower.”

Participants were then spawned in the virtual environment immediately in front of the first landmark (Laundromat), and instructed to “Find the Laundromat.” Once they walked within a 1-meter radius of a white and red label positioned in front of the landmark (see Figure 3), the sequence of 40 successive landmark-to-landmark navigation trials was activated. The trials were always in the same order, (i.e., Trial 1: Laundromat to Pet Store, Trial 2: Pet Store to Gym), and each of the 21 landmarks was used twice as an origin and/or destination (with one exception, Market, which was used once).

Eight of the trials used 0° angular error. The other 32 trials were evenly divided among the eight error conditions (-60° , -45° , -30° , -15° , 15° , 30° , 45° , 60°); negative error was leftward from the avatar’s facing direction, and positive error was rightward. The error angle was calculated as the difference between the true vector between starting position and goal destination, plus or minus the condition-specific error. An example is depicted in Figure 1. Error conditions were randomly assigned to each landmark-to-landmark trial, and then rotated through

trials across participants. For instance, if Trial 1 was 0° angular error for participant 1, then it was 15° angular error for participant 2, 30° angular error for participant 3, and so forth.

Participants had unlimited time to reach each goal destination. Upon reaching a goal, they were probed for their trust in the system, responding on a scale ranging from 1-7. After the set of 40 landmark-to-landmark trials, they finished the experiment.

2.7 Data Processing & Analysis

One participant dropped due to simulator sickness (nausea), leaving 29 full data sets for analysis.

The Santa Barbara Sense of Direction scale was reverse-scored as required and summed to create a composite sense of direction score (Hegarty et al., 2002).

For navigation output, we calculated each participant's path efficiency and time efficiency for each of the 40 navigation trials. For path efficiency, we related their path length (denominator) to optimal path length as calculated via the A* pathfinding algorithm (numerator) (Hart et al., 1968). For time efficiency, we related their navigation time in seconds (denominator) to optimal navigation time (numerator) calculated via the A* pathfinding algorithm with a fixed rate of advance matching the virtual walking speed. Path and time efficiency scores thus ranged from infinitely approaching 0 (low efficiency) to 1 (highest efficiency). Note that path and time efficiency tend to be highly correlated; deviations from this correlation are in the form of brief pauses (perhaps to look around, reorient), which result in reduced time efficiency without corresponding reductions in path efficiency.

For analysis, after confirming they did not differ, negative and positive angular error conditions were collapsed, resulting in 5 levels of the within-participants factor, Angular Error (5: 0°, 15°, 30°, 45°, 60°). We then used a single-factor repeated-measures ANOVAs to examine

Angular Error influences on path and time efficiency. To examine Angular Error influences on trust ratings, we used a non-parametric Friedman test.

3. Experiment 1 Results

Primary results of path efficiency and subjective trust ratings are depicted in Figure 4.

3.1 Angular Error & Path Efficiency

An ANOVA examining path efficiency as a dependent variable revealed a main effect of Angular Error, $F(4, 112) = 232.49, p < .001, \eta^2 = .89$, with lower path efficiency in higher angular error conditions. Four follow-up paired t-tests demonstrated significant differences between the control (0° error) and each of the four error conditions (all p 's $< .001$).

3.2 Angular Error & Time Efficiency

Path and time efficiency were highly correlated ($r = .90$). An ANOVA examining time efficiency as a dependent variable revealed a main effect of Angular Error, $F(4, 112) = 215.18, p < .001, \eta^2 = .88$, with lower time efficiency in higher angular error conditions. Four follow-up paired t-tests demonstrated significant differences between the control (0° error) and each of the four error conditions (all p 's $< .006$).

3.3 Angular Error & Subjective Trust

A Friedman test examining trust ratings as a dependent variable revealed an effect of Angular Error $\chi^2(29) = 77.98, p < .001$. As depicted in Figure 4, there were lower trust ratings in higher angular error conditions. Four follow-up tests demonstrated a significant difference between the control (0° error) and the 30° , 45° , and 60° error conditions (all p 's $< .002$). The 15° condition did not differ from 0° ($p = .18$).

3.4 Individual Differences

To assess whether participant gender, video game experience, and/or sense of direction influenced angular error effects on path efficiency, we conducted a mixed analysis of covariance (ANCOVA). The ANCOVA examined whether gender and video game experience (between-participants factors) and/or sense of direction (covariate), influenced the effect of angular error on path efficiency; none of these variables interacted with angular error (all p 's > .13).

4. Experiment 1 Discussion

The present experiment examined the influence of introducing 0 to 60 degrees of angular error into a simulated augmented reality navigation guidance beacon. We found that path efficiency declined significantly in each of the four angular error conditions. In other words, even 15° of angular error negatively influenced path efficiency. In contrast, though 15° of angular error influenced path efficiency, it did not significantly influence perceived trust, which did not decline significantly until 30° of angular error. Thus, a dissociation emerged regarding objective versus subjective impacts of angular error in an augmented reality navigation device. Path efficiency is negatively impacted with 15° angular error, but participants may not be subjectively aware of this impact until angular error is larger.

5. Experiment 2 Introduction

Our first experiment demonstrated a significant impact of 15° angular error on path efficiency, but it is unclear where exactly this difference emerges between 0° and 15°. It is also unclear where between 15° and 30° the impact on perceived trust emerges. To further specify the impact of angular error on path efficiency and perceived trust, our second experiment manipulated angular error in increments of 5° between 0°, 5°, 10°, 15°, and 20°. We hypothesized that we would replicate the results of Experiment 1, with a significant decline in

path efficiency at 15° error. Our results will also better specify where exactly the impact of angular error on path efficiency and trust emerge.

6. Experiment 2 Method

6.1 Participants

A total of 30 Tufts University students (15 male, 15 female, $M_{\text{age}} = 22.2$, 8 video gamers, 22 non-gamers) participated for monetary compensation (\$20USD). The sample did not contain any participants who were tested in Experiment 1. All testing procedures were approved by the institutional review board of Tufts University, with secondary approvals by the U.S. Army Human Research Protections Office.

6.2 Design, Setting, Apparatus, Instruments, Procedure, & Data Processing/Analysis

A within-participants repeated-measures design was used, involving exposing each participant to five directional error conditions (0°, 5°, 10°, 15°, and 20° angular error). The remainder of the design, setting, apparatus, procedure, and data processing and analysis were identical to Experiment 1.

7. Experiment 2 Results

Primary results of path efficiency and subjective trust ratings are depicted in Figure 5.

7.1 Angular Error & Path Efficiency

An ANOVA examining path efficiency revealed a main effect of Angular Error, $F(4, 116) = 10.06$, $p < .001$, $\eta^2 = .26$, with lower path efficiency in higher angular error conditions. Four follow-up paired t-tests demonstrated a significant difference between the 0° error and 10° error conditions ($p = .012$), and between the 0° and 15° and 0° and 20° error conditions (p 's $< .01$). The 5° and 10° conditions differed ($p = .04$), but 5° did not differ from 0° ($p = .47$).

7.2 Angular Error & Time Efficiency

Path and time efficiency were highly correlated ($r = .70$). An ANOVA examining time efficiency as a dependent variable revealed a main effect of Angular Error, $F(4, 116) = 5.09, p < .001, \eta^2 = .15$, with lower time efficiency in higher angular error conditions. Four follow-up paired t-tests demonstrated significant differences between the control (0° error) and the 10° , 15° , and 20° conditions (all p 's $< .022$). The 5° did not differ from 0° ($p = .48$).

7.3 Angular Error & Subjective Trust

A Friedman test examining trust ratings as a dependent variable revealed an effect of Angular Error $\chi^2(30) = 22.26, p < .001$. As depicted in Figure 5, there were lower trust ratings in higher angular error conditions. Four follow-up tests demonstrated a significant difference between the 0° error and the 15° and 20° error conditions (all p 's $< .009$). The 5° and 10° conditions did not differ from 0° (p 's $> .22$).

7.4 Individual Differences

An ANCOVA examined whether gender and video game experience (between-participants factors) and/or sense of direction (covariate), influenced the effect of angular error on path efficiency; none of these variables interacted with angular error (all p 's $> .08$).

8. Experiment 2 Discussion

The present experiment examined the influence of introducing 0° to 20° of angular error, in 5° increments, into a simulated augmented reality navigation guidance beacon. Replicating and extending Experiment 1 results, we found that path efficiency declined significantly at 10° and continued to decline through 15° and 20° . Trust showed a significant difference at 15° and 20° , this experiment's two highest angular error conditions. Thus, again we find evidence for a

dissociation between objective and subjective impacts of angular error, with an objective impact emerging at lower angular error (10°) relative to a subjective impact (15°).

9. Experiment 3 Introduction

Our second experiment demonstrated a significant impact of 10° angular error on path efficiency, and 20° angular error on subjective trust. A difference in path efficiency emerged somewhere between 5° and 10° angular error. To further specify where exactly the path efficiency effect emerges, we conducted a final experiment that manipulated error in increments of 1° between 6° and 10° (6°, 7°, 8°, 9°, 10°). We hypothesized that we would replicate the path efficiency results of Experiment 2, with a significant decline in path efficiency at 10° error, and better specify the error at which path efficiency first declines.

10. Experiment 3 Method

10.1 Participants

A total of 30 Tufts University students (10 male, 20 female, $M_{\text{age}} = 22.7$, 5 video gamers, 25 non-gamers) participated for monetary compensation (\$20USD). The sample did not contain any participants who were tested in Experiments 1 or 2. All testing procedures were approved by the institutional review board of Tufts University, with secondary approvals by the U.S. Army Human Research Protections Office.

10.2 Design, Setting, Apparatus, Instruments, Procedure, & Data Processing/Analysis

A within-participants repeated-measures design was used, involving exposing each participant to five directional error conditions (6°, 7°, 8°, 9°, and 10° angular error). The remainder of the design, setting, apparatus, procedure, and data processing and analysis were identical to Experiment 1.

11. Experiment 3 Results

Primary results of path efficiency and subjective trust ratings are depicted in Figure 6. For comparison purposes we include the 0° and 5° conditions from Experiment 2.

11.1 Angular Error & Path Efficiency

An ANOVA examining path efficiency revealed a main effect of Angular Error, $F(4, 116) = 2.58, p < .05, \eta^2 = .08$, with lower path efficiency in higher angular error conditions. Four follow-up paired t-tests demonstrated a significant difference between the 6° error and 9° error conditions ($p = .045$), and between the 6° and 10° error conditions ($p < .001$).

11.2 Angular Error & Time Efficiency

Path and time efficiency were highly correlated ($r = .80$). An ANOVA examining time efficiency as a dependent variable revealed a main effect of Angular Error, $F(4, 116) = 2.59, p < .05, \eta^2 = .08$, with lower time efficiency in higher angular error conditions. Four follow-up paired t-tests demonstrated significant differences between the 6° error and 10° error conditions ($p = .03$). The difference between the 6° and 9° conditions was marginal ($p = .07$).

11.3 Angular Error & Subjective Trust

A Friedman test examining trust ratings as a dependent variable revealed no effect of Angular Error $\chi^2(30) = 3.4, p = .49$.

11.4 Individual Differences

An ANCOVA examined whether gender and video game experience (between-participants factors) and/or sense of direction (covariate), influenced the effect of angular error on path efficiency; none of these variables interacted with angular error (all p 's $> .05$).

11.5 Follow-up Analysis: Environment Learning

It could be the case that introducing angular error into beacons would influence the development of cognitive maps during navigation. To examine this possibility, we compared the three experiment's slopes of path efficiency change over the course of the 20 trials. To do so, we conducted three linear regressions asking whether trial order (1-20) predicted path efficiency. In Experiments 1 and 2, there was no significant trend of increasing path efficiency over the course of the 20 trials (p 's $> .18$, R^2 's $< .05$, β 's $< .22$). In Experiment 3, however, there was a small but significant increase in path efficiency over the course of the 20 trials, $t(39) = 2.09$, $p < .05$, $R^2 = .10$, $\beta_{\text{std}} = .32$.

12. Experiment 3 Discussion

The present experiment examined the influence of introducing 6° to 10° of angular error, in 1° increments. Path efficiency rates were highly similar between the 5° (Experiment 2) and 6° (Experiment 3) conditions; indeed follow-up independent samples t-tests demonstrated that 5° ($M = .8384$) and 6° ($M = .8382$) conditions produced nearly identical means across Experiments 2 and 3 ($p = .99$). Only at 9° of angular error did path efficiency decline significantly in the present experiment.

As would be expected given Experiment 2 results demonstrating a decline in trust only at 20° angular error, the present error conditions did not impact trust ratings. Thus, as in Experiments 2 and 3 we find evidence for path efficiency declining at lower angular errors than subjective trust. Specifically, path efficiency in urban environments appears to decline with approximately 9° of angular error, and trust declines somewhere between 16 - 20° of angular error.

12. General Discussion

Three experiments successively approximated objective and subjective tolerance for angular error introduced into a simulated augmented reality system designed to aid navigation through a virtual urban environment. Our intention was to provide an examination of how angular error in a beacon-based navigation guidance system would influence the efficiency with which users could navigate, and the extent to which they would continue trusting the system to effectively guide them to destinations.

12.1 Overall Results

Five primary findings emerged from the experiments. First, we found ample evidence that a highly accurate beacon-based navigation aid depicting the general direction and distance to a destination provides effective guidance in an urban environment. Indeed participants were able to navigate with, on average, 85% efficiency relative to optimal routes determined with a pathfinding algorithm. This is substantially higher efficiency than pilot experimentation conducted in our laboratory demonstrating that participants produce path efficiency approximating 39% in the absence of any guidance. In other words, paths were over twice as long in the absence of guidance. Thus, beacon-based visual overlays appear to provide effective navigation guidance through an urban environment. It is likely that beacon-based guidance will be of highest utility for pedestrians navigating on foot; indeed in-vehicle navigation poses a novel set of requirements given route affordances (e.g., one-way streets, detours).

Second, we found evidence that path efficiency shows only minor reductions with angular error rates of 8° or lower, with significant reductions only emerging with 9° of error. Of course, this result should be considered a first heuristic for guiding system requirements, and should be considered only within the context of urban navigation where the majority of

intersections (and thus turns) are orthogonal. It could be the case that relatively open, expansive environments (or urban environments with non-orthogonal intersections; e.g., Boston, MA) will elicit different effects of angular error. Furthermore, though our virtual environment was considerably large relative to many others used in the cognitive sciences, the farther a user needs to travel the more influence angular error may have on path selection, particularly early in a route.

Third, we found evidence that subjective trust in the system only shows significant decreases with particularly high levels of angular error exceeding 16-19°. Again, users may be more likely to acknowledge system error in relatively open, expansive environments where an objective becomes visible as it is approached (yet the system suggests a markedly different direction). Fourth, in comparing objective and subjective impacts of angular error it has become clear that objective impacts on path efficiency emerge at considerably lower error levels relative to subjectively experienced impacts. This is an important consideration for evaluating trade-offs between registration capabilities, path efficiency, and user acceptance of an imperfect system. Though the present study was not designed to reveal the cues participants used to recognize angular error (and thus reduce trust ratings), we can make a few assumptions. As participants develop a cognitive map of the environment through extended experience, an inaccurate beacon's suggested direction may be incongruent with the direction computed from a cognitive map. In those cases, one would imagine that participants become cognizant of the angular error and, therefore, exhibit reduced trust. However, in the absence of a well-developed cognitive map, this process seems unlikely. A second possibility is that angular error became perceptible to participants once the goal landmark was within their line of sight. Particularly at farther distances, angular errors exceeding 15-20 degrees are very apparent and likely noticed by

participants. This is similar to perceptible registration errors perceived and explicitly acknowledged by participants using other augmented reality systems (Madsen and Stenholt, 2014).

Finally, a follow-up analysis comparing the slope of path efficiency change over the course of the 20 experimental trials demonstrated that only in Experiment 3 did participants show improved path efficiency over time. This result suggests that in cases of minimal angular error introduced into a beacon system, participants are more likely to develop cognitive maps of an experienced environment. Ultimately, these cognitive maps may prove valuable during future navigation without system availability (Chrastil and Warren, 2013; Gardony et al., 2015). This finding suggests that large registration errors not only limit path efficiency and trust, they also can negatively impact environmental learning during navigation. Indeed Experiment 3 had angular error ≤ 10 degrees, in contrast to the first two experiments which exhibited relatively high angular error ≤ 60 degrees and ≤ 20 degrees, respectively.

12.2 Implications for Application

As hand-held and eyewear-mounted augmented reality systems become increasingly prevalent, it is important to understand how system-level parameters influence utility and user acceptance. One of the most promising futures for augmented reality is in personal wearable computing, with systems providing new capabilities for tagging and describing locations, guiding navigation, conveying messages, and 3D visualization (Hughes et al., 2005). Applications requiring the precise placement of virtual landmark tags are particularly challenging in outdoor environments due to tracking imprecision and resulting registration errors (Carmigniani et al., 2011; Foxlin et al., 2015). Navigation guidance poses a particular problem given its reliance on precise landmark tagging and real-time tracking of user orientations relative

to landmark positions, and error accumulates in the system as either or both of these exhibits imprecision.

The present study provides a novel view of the trade-offs between registration accuracy and user performance in navigation tasks. Emerging systems intending to afford navigation efficiency will benefit from cognizance of how angular error influences performance on behalf of users. In urban settings, the present results suggest that the design and development of augmented reality systems should ensure registration accuracy below approximately 9° of horizontal angular error. Above that point, path efficiency becomes significantly impaired and can lead a user temporarily astray from intended destinations; in some cases, even with higher angular error rates path efficiency may still exceed that seen in the absence of guidance. Whereas reduced path efficiency among tourists navigating between points of interest may not prove particularly detrimental to the task or user, the same reductions may prove disastrous among military personnel navigating on foot through unfamiliar city areas. Thus, system designers and users will need to cater registration accuracy requirements to contexts and task demands; for instance, systems that continually monitor and assess registration error accumulation (Foxlin et al., 2015; Miura et al., 2015) could establish approximate thresholds for providing users with feedback regarding variable system reliability (Chavaillaz et al., 2016).

Regarding trust in augmented reality, as users experience higher registration errors (i.e., between 16 - 20°) they become acutely aware of system limitations. In the present study this resulted in reliable reductions in rated trust in the system to guide them to destinations. System registration inaccuracies appear to modulate trust and, as noted by (Parasuraman and Wickens, 2008), are very likely to reduce user dependence on the system. Indeed the magnitude and frequency of angular errors will dynamically influence trust over the course of system adoption

and continued use (Chavaillaz et al., 2016; Lee and Moray, 1994; Manzey et al., 2012). Thus, while some limitations in terms of path efficiency may be tolerated among particular users and tasks (like with tourists), if system faults become perceptible it is very likely that users will decrease dependence on the system and may eventually discontinue its use.

12.3 Implications for Theory

To successfully orient oneself in an environment, navigators continuously update their position and heading relative to a goal location. In particular, navigators tend to focus on local geometric variance in an environment such as turns, path openings, and occlusions (Wiener et al., 2012), using these to guide decisions that enable orientations and route plans congruent with the global direction of a goal location (Hölscher et al., 2011). Navigating under conditions of uncertainty or in highly novel environments can introduce reliable shifts in strategy reliance as navigators become more familiar with an environment (Brunyé et al., 2015); in general, people shift from relying on local landmarks and turns to relying on relatively global directions and the overall structure of an environment (Golledge, 1995; Thorndyke and Hayes-Roth, 1982). While systems providing turn-by-turn directions may encourage a focus on local features and turn directions, beacon-based systems introduce the possibility of providing a constant global awareness that is rarely imparted by other navigation aids. In this manner, global aids may provide a reliable allocentric coordinate system that may facilitate some types of spatial knowledge acquisition. This possibility remains to be tested, particularly relative to turn-by-turn directions.

Recent research with navigation aids has demonstrated important trade-offs between the extent of guidance imparted by a system, users' engagement and attention toward an environment, and resulting spatial memory (Bakdash et al., 2004; Chrastil and Warren, 2013;

Gardony et al., 2015, 2013). The notion is that while navigation aids can increase the efficiency with which a user reaches a destination, they also can carry detrimental implications for spatial memory. Thus, when a user can no longer rely on the system they will show markedly lower navigation performance relative to peers who initially experienced an environment without the system. This research demonstrates a need for identifying systems that better balance navigation efficiency and resulting spatial memory, for instance by indicating only the general direction to a destination and requiring users to make active decisions regarding optimal turning locations and directions. From a theoretical perspective, such systems will increase attention to the environment including its features and structure, ultimately promoting the development of spatial memories that can subsequently serve navigation tasks in the absence of an aid. The present learning data suggest that this may only be the case when beacons are characterized by relatively low angular error.

12.4 Limitations

Precisely because commercially available augmented reality systems showcase dynamic registration error during use, the present study leveraged desktop virtual environments to simulate a highly reliable augmented reality system. This made it possible to control and manipulate angular error without additionally needing to track and account for spontaneous dynamic system error (Tlauka, 2007). While this made it possible to control for system variability and reliably manipulate angular error, it also decreased real-world applicability. Indeed angular error in real-world conditions is unlikely to be numerically or directionally systematic; rather, it is likely dynamic and varying not only in magnitude but also direction (i.e., right, left, up, down relative to a user). It is unclear how such dynamic error might interact with system utility or user trust, but continuing research will explore such scenarios. Furthermore, it is

unlikely that a single strict threshold exists for objective or subjective impacts of angular error on navigation performance or trust. More likely, the impact of angular error will vary as a function of environment context, tasks, perceptible versus imperceptible goal destinations, and participants' attention and reliance on the system. Thus, our data provide basic context- and task-specific approximations rather than strict thresholds.

We chose to explore the influence of angular error in urban navigation because urban environments in particular introduce highly variable error into location and orientation tracking (Duncan et al., 2013). Of course, this methodological feature may limit the applicability of our findings to other environment types, such as suburban or rural. Though this remains to be tested, we predict that lower density environments with lengthier path segments will show path efficiency and trust decreases at even lower angular error levels. At farther distances angular error has more potential to decrease path efficiency, and as a user approaches a perceptible destination they will likely acknowledge angular error rates lower than 16-20°.

An additional direction for continuing research is to use a between-participants manipulation of angular error in order to isolate user trust in a system as a whole. The present research examined only user trust in system reliability on a single trial, given that across trials it would be difficult for a participant to develop a cohesive understanding of system reliability. Furthermore, there are unknown consequences of possible carry-over effects from trial to trial in the present design. Continuing research may consider assessing trust in a single system with dynamic error over time, but within particular ranges. Thus, the limitations of the present study point to several potential directions for our continuing research.

12.5 Conclusions

In conclusion, the present study uniquely explored the influence of static angular error in navigation guidance system presented on a simulated augmented reality overlay. We demonstrated reductions in path efficiency on behalf of navigators when angular error exceeded 8° , and reductions in subjective trust when error exceeded $16-20^{\circ}$. Influences on the objective path efficiency measure consistently emerged at lower angular error levels relative to influences on subjective trust. These results hold implications for the design, development, and deployment of augmented reality for guiding navigation through urban environments, and theoretical implications for optimizing global awareness and spatial knowledge acquisition.

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Figure Captions

Figure 1. An overhead view of the virtual environment, with each of the 21 goal landmarks indicated and labeled. An example vector indicating 9 degrees of positive or negative angular error is depicted (red lines) for the Laundromat to Pet Store trial. This is compared to a 0 degree vector relating the origin and destination (blue line).

Figure 2. A view from within the virtual environment. Navigation beacon is depicted center left, with a floating polygon indicating the direction of the named landmark, with current distance indicated.

Figure 3. A view from within the virtual environment. Navigation beacon is depicted at center, with a floating polygon indicating the direction of the named landmark, with current distance indicated.

Figure 4. Experiment 1 mean path efficiency (left y axis) and trust ratings (right y axis) for each of the five angular error conditions. Error bars depict standard error of the mean.

Figure 5. Experiment 2 mean path efficiency (left y axis) and trust ratings (right y axis) for each of the five angular error conditions. Error bars depict standard error of the mean.

Figure 6. Experiment 3 mean path efficiency (left y axis) and trust ratings (right y axis) for each of the five angular error conditions; for comparison, also included are Experiment 2 path efficiency and trust ratings for 0° and 5° angular error. Error bars depict standard error of the mean.

Figure1

Figure2

Figure3

Figure4

Figure5

Figure6