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A mirror in the sky: assessment of an augmented reality method for depicting navigational information

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ABSTRACT

We investigated the efficacy of a novel augmented reality (AR) navigation display called Mirror in the Sky (MitS). AR displays can reduce the distance between virtual imagery content and the user's view of the environment but may have limited benefit for depicting map-based survey information. MitS presents a simulated mirror in the upper visual field, which reflects the topographic layout of the terrain in front of the user. In our experiment, 28 participants used MitS and a track-up Map in virtual reality to perform a *route confirmation* task, which required participants to decide whether a route could be successfully navigated. A post-trial *threat location* recall task examined spatial awareness. On that task, accuracy, duration, and subjective workload measures favoured the Map. However, participants with virtual reality experience made more accurate route confirmation decisions with MitS than the Map.

Practitioner summary: We compared an augmented reality display called Mirror in the Sky (MitS) to a conventional electronic map for route confirmation and threat location tasks. Although the electronic map showed advantages over MitS on some measures, users with some VR experience performed route confirmation more accurately with MitS than a map.

Abbreviations: MitS: mirror in the sky; AR: augmented reality; HDD: head-down display; HUD: head-up display; FFOV: forward field of view; GPS: global positioning system; FoR: frame of reference; IAC: information access cost; VR: virtual reality; ANOVE: analysis of Variance

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Introduction

As augmented reality (AR) technology continues to improve, the reduction in size and weight of head-mounted displays makes AR use more viable in a variety of environments (Dey et al. 2016; Livingston, Ai, and Decker 2018). A key difference between AR and other display technologies is that AR can portray virtual imagery so that it appears to be a part of the user's surrounding environment, connecting that information to environmental features in the forward field of view (FFOV). Such integration can be particularly useful in the context of navigation, as when AR is used to combine a recommended route with the user's forward view (Bark et al. 2014).

Traditionally paper maps have been used to navigate unfamiliar environments. Such maps are gradually being replaced by electronic maps, commonly shown on handheld devices for pedestrians or head-down displays (HDDs) in vehicles. Electronic maps can also be shown using head-up displays (HUDs), which can place the map or related route information in the user's FFOV (e.g. Yeh et al. 2003). As such, showing map-based survey information in a HUD represents a potentially important AR application, though the presentation needs to be considered, such that the map does not create clutter in the user's FFOV (Yeh et al. 2003).

This article will consider applications of navigation displays in the military domain (e.g. Aretz 1991; Hollands and Lamb 2011; Thomas and Wickens 2006; Yeh et al. 2003); specifically, the problem of a dismounted soldier navigating an urban environment. While soldiers have traditionally used paper maps and a compass, global positioning systems (GPS) and digital technology can provide updated information and alerts that are directly tied to surroundings and position. In addition, AR can present map-based survey information in a hands-free manner, allowing soldiers to attend to their surroundings or perform other tasks.

In this paper, we investigate the impact of information presentation in navigation displays and describe an experiment conducted to investigate the

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performance of a novel AR display relative to a 2D electronic map. We first consider how the display of spatial information can support navigation. Then we discuss the costs of accessing spatial information presented in different locations. Finally, we describe the AR display and consider its potential benefits before describing our experiment.

Spatial information for navigation

In the context of navigation, a display can present spatial information in different formats: (i) survey, providing structural or layout information from a top-down or bird's eye view perspective, (ii) route, providing response-based information for travel to a destination, or (iii) landmark, highlighting points of interest (based on Siegel and White 1975). AR navigation displays commonly present users with route or landmark cues (e.g. Jose, Lee, and Billinghurst 2016). These cues are useful for tasks with well-defined goals but may not support more complex tasks like route planning or acquiring survey knowledge (Thorndyke and Hayes-Roth 1982). Such tasks involve matching objects or structures in the environment to those in the display.

Survey information is often presented as a two-dimensional map. Commonly presented on smartphones and GPS devices, electronic maps, like paper maps, are scaled at a fraction of the actual size. Maps use a different frame of reference (FoR), a world-referenced frame, instead of the user's ego-referenced frame. A series of cognitive transformations and comparisons are sometimes required to relate environmental features to information displayed on a map for self-location and orientation (Wickens, Vincow, and Yeh 2005).

FoR transformations can produce performance decrements such as decreased accuracy, increased response time, and/or increased workload (Wickens 1999; Wickens, Keller, and Small 2010). Generally, the decrements become greater as the difference between FoRs increases. 'Difference' in this context can refer to the number and magnitude of transformations required to relate the FoRs, including rotation, scale, number of dimensions, or shape distortions (Wickens, Vincow, and Yeh 2005). Small changes in presentation that do not affect the FoR, such as tilting a map, are expected to have negligible performance costs (Wickens, Keller, and Small 2010).

For display-aided navigation, the user must extract and relate relevant information from the environment and the display. Examples include determining which street in the environment the navigation system is indicating for a turn or looking for a landmark to determine one's orientation relative to a map. In the military context, this may include determining the location of threats in the environment and comparing those locations to a planned route on a display.

Display differences can also be considered in terms of their informational and computational equivalency (Simon 1978). Displays can be considered informationally equivalent if transformations between them result in no loss of information, such that one can be constructed from the other. Computational equivalence is achieved if the same inferences can be drawn from both displays with approximately the same effort and speed (Larkin and Simon 1987). If a navigator is given a map, a route drawn on it can be considered informationally equivalent to a written list of directions. They are not computationally equivalent since the navigator must integrate information from multiple sources in the latter case.

Information access cost

Information access cost (IAC) refers to the cost (commonly physical or mental effort) associated with retrieving information from a source or area of interest (Wickens and McCarley 2008). Physical IAC is expected to increase with distance between areas of interest in the visual field (e.g. looking up (an angular distance $< 90°$) would elicit a lower cost than looking behind (an angular distance approaching $180°$)). Areas of interest can be as specific as a particular instrument, or as broad as an entire display (Wickens and McCarley 2008). Users tend to make fewer information seeking actions as access cost increases (Fu and Gray 2006). Research has shown that head orientation predicts glance location, particularly when the user is stationary (Muñoz et al. 2015), and glance changes can be characterised as information seeking actions.

Users may rely more on working memory than on displayed information as IAC increases (Ballard, Hayhoe, and Pelz 1995). Gray and Fu (2004) found that participants increasingly relied on error-prone knowledge in the head over more reliable knowledge in the world as the cost to access a display increased. Similarly with navigation displays, users may over-rely on their working memory representation of the environment and check the display less frequently as IAC increases.

A HUD presents information near the user's FFOV. For example, it could display information about a landmark next to the landmark. Therefore a HUD reduces the separation between two areas of interest.

Figure 1. Mirror in the Sky (MitS) display with self-position marker (red circle) in Virtual Environment.

As such, a HUD should have lower IAC than a HDD. Studies have found improved performance in HUD conditions relative to HDDs (see Fadden, Ververs, and Wickens 1998 for a meta-analysis; Smith et al. 2015) and performance with HUDs improves as the distance between information sources within the HUD is reduced (Martin-Emerson and Wickens 1992). The tasks used in these studies generally did not require survey information and were response-based in nature, such as direction following (e.g. Jose, Lee, and Billinghurst 2016; Kim and Dey 2009), or target search or following (Fadden, Ververs, and Wickens 1998; Smith et al. 2015; Yeh et al. 2003). HUDs in those studies provided users with route or landmark cues, but not survey information.

Other work has considered different presentations of head-up survey information. One method is to appear to distort the environment by curving a display (Kim and Dey 2009) such that the display appears to rise out of the ground, giving the illusion that the flat environment is a wall in front of the user. Pasewaldt, Trapp, and Dollner (2011) created a similar effect in a virtual environment by curving the environment to appear like a wave, putting a portion of the bird's-eye view in front of the user. While these presentations provide a novel way to display head-up survey information, they deform the environment and/or display, and can reduce visibility such that they are not informationally equivalent to current map displays.

Survey information near the FFOV

In this article, we introduce a novel method for presenting survey information called Mirror in the Sky (MitS; Figure 1). MitS presents a simulated mirror-like surface in the user's upper to forward visual field which reflects the topographic layout of the terrain in the environment. The shape and position of the mirror surface can be adjusted to change the appearance of survey information. For example, although the scale of the map is world-sized, the scale perceived by the user will depend on the height, shape, and angle of the mirror.

The concept of MitS was conceived by Uncharted Software Incorporated and is currently in development there (Kapler, King, and Segura 2019; Oculus Info Inc. 2013). MitS is initially intended to be presented through a head mounted AR display for users on foot navigating a real environment. Because an AR version was still in development, a MitS v1.0 prototype in a virtual reality (VR) testbed was developed for proof of concept and experimentation.

The cognitive processes required to relate a user's view of MitS to the environment should be different from those used with a map. With a map, a scaling transformation might be necessary, 'stretching' or 'compressing' distances to compare information in the map and the environment. This scaling is not required with MitS. However, with MitS, the viewer will need to interpret how the shape and position of the simulated mirror reflects information in the environment, which will determine the difficulty of the FoR transformation between the display and environment. When looking at an object in a real environment, generally the closer it is, the lower it is in the viewer's FOV. As an object moves further away in the environment, it tends to move up towards the horizon (among other size and

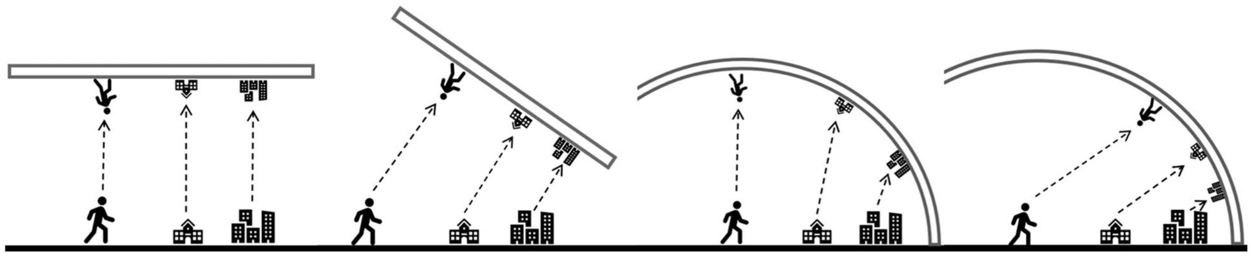

Figure 2. Different possible mirror presentations for MitS (left to right: flat, tilted, dome, dome with offset).

motion cues). Since MitS reflects information, the viewer may see the opposite relationship, where a closer object is generally higher and an object moving away produces a downward movement towards the horizon (Figure 2).

The position, scale, and orientation of MitS might reduce the need for mental translation, rescaling, or rotation when comparing the display to the environment, relative to comparing a 2D map to the environment. MitS' reflection and track-up orientation take advantage of linear perspective, such that as objects in the display get further away, they decrease in size, just as in the real environment. Users should thus be able to more easily compare information in the display and environment with MitS than with conventional maps. MitS' position above the viewer may also reduce clutter effects when compared to HUDs presenting maps near the FFOV (e.g. Yeh et al. 2003). These advantages may persist when compared to maps that perform some of the cognitive transformations, such as automatic orientation rotation with track-up maps. By providing users with survey information from a perspective similar to their own view of the environment, MitS may improve a user's ability to perform complex navigation tasks requiring survey information.

Recalling spatial information

The presentation format of spatial information can also affect how that information is stored in memory (e.g. orientation dependence, McNamara 2003). Directional navigation aids have been found to impair spatial memory (Gardony et al. 2013), though the format and presenter of the directional information can have an effect. Antrobus, Burnett, and Skrypchuk (2016) found that when directions were provided by an informed passenger, participants were later able to more accurately identify the direction of the route start point and sketch a more detailed map than when directed by a SatNav system.

Ishikawa and Takahashi (2014) found that participants performing a wayfinding task had better recall of their surroundings when using a paper map without directions compared to a mobile device with a route or directional arrow. Participants spent more time looking at the display (greater dwell time) when they had either mobile device than with the paper map, suggesting that information seeking behaviour had varied with display presentation.

These studies show that spatial information communicated in more dynamic displays that produced longer dwell times resulted in poorer recall when compared to conventional 2D maps. Given the novel and dynamic presentation of MitS, we might expect that users will have longer display dwell times and poorer recall of their surroundings.

Virtual reality and navigation

To investigate how MitS could work under ideal conditions without technical challenges like 'resolution, FOV, position tracking, and outdoor contrast' (Kapler et al. 2019, 1), a virtual environment simulation was developed for testing. VR has previously been shown to be an effective substitute for AR displays in experimentation (Deb et al. 2017; Durgin and Li 2010).

One limitation of VR presentation is that users may have reduced spatial understanding relative to real environments: for example, participants underestimate distances in virtual environments when fidelity is not photorealistic and presence is low (Interrante et al. 2008). However, experience with VR systems may help to reduce such biases. First-time VR users are more susceptible to simulator sickness and may require some exposure to adapt to the differences between virtual and real environments, particularly when presented with a head mounted display (Buker, Vincenzi, and Deaton 2012; Johnson 2005). Such users can experience conflicting sensory and motion cues from visual and vestibular systems. More experienced VR users may have adapted to those conflicting cues (Johnson 2005); thus, it is important to consider participants' prior exposure to VR. Furthermore, the ultimate implementation of MitS as an AR display will also involve the use of virtual imagery and as such VR experience should also be relevant in that context.

Previous research into aided navigation has compared different FoRs (e.g. Aretz 1991; Hollands and Lamb 2011; Wang and Milgram 2009; Wickens, Vincow, and Yeh 2005), used different display media and/or presentation positions (Jose, Lee, and Billinghurst 2016; Smith et al. 2015), and has presented different types of information (Yeh et al. 2003). But to our knowledge, no study has considered presenting survey information with mirrored imagery like MitS. In the current experiment, we compare MitS to a conventional track-up Map on navigation-related spatial tasks. Since the focus is on features that are represented by MitS, the maps used in both displays will maintain informational equivalence, so that performance differences obtained are a result of computational differences produced by differing display presentations. A track-up map was selected as a basis for comparison since it is more computationally similar to the presentation of MitS than a north-up map. We investigate the unique properties embodied by MitS on two tasks with potential military applicability.

Our interest was primarily in how well each display supported participants in making initial assessments of a situation without the requirement of locomotion. We used two stationary tasks: a *route confirmation* task that required participants to relate information in the display and the environment in order to make decisions about a route, and a *threat location* task that tested participants' recall of the environment once the route confirmation task had been completed (cf. Hollands and Lamb 2011).

Hypotheses

For the route confirmation task, participants were expected to require less cognitive translation and rescaling (i.e. a lower IAC) with MitS relative to a Map in order to compare information from the display and environment. Hence, performance measures and subjective workload ratings were expected to favour MitS over the Map. For the threat location task, performance and ratings were expected to favour the Map over MitS on one or more dependent measures. The Map was expected to benefit from the familiarity of its top-down FoR on a task that required participants to recall survey information. For both tasks, we also expected that participants with less VR experience will perform better with a familiar 2D Map than with MitS.

Methods

Participants

Thirty (30) University of Toronto students (age: M = 25.3, SD = 3.06; 26 males, 4 females) were recruited by an email sent to the graduate student mailing list in the Department of Mechanical and Industrial Engineering. Our recruitment did not screen based on gender, so the gender disparity in our participant sample may represent a male-dominated participant pool of engineering students, the recruitment messaging, which focussed on navigation and VR, or both.

An introductory survey collected demographic information, including questions about previous experience with VR and propensity for simulator sickness. Participants were asked to identify the approximate number of sessions they had had with head-mounted VR. Individuals who had previously experienced simulator sickness were asked not to participate to avoid being at risk of any sickness recurrences. Participants wore corrective lenses if required. Participants were paid $20 CAD per hour, and the experiment took approximately 2 h to complete. Data from two male participants were later dropped due to poor performance (task accuracy was outside of three standard deviations) and a lack of task engagement (as noted by the experimenter), producing an N of 28 (age: M = 25.4, SD = 3.13).

Of the 28 participants, 14 had VR experience and 14 were first-time VR users. Although much of the first group had only limited exposure to VR, (some as little as an hour and just one having used VR more than five times) we refer to this group as VR-experienced for simplicity.

Apparatus

VR was used to simulate a navigation display in a real environment. The simulated displays (Figures 3 and 4) were MitS and a Map. A red self-marker in the display showed the current position. Participants could not manipulate the displays directly, but both displays were track-up, rotating with the participants as they turned. Participants could access all relevant information in both conditions through eye and head movements.

The simulation was rendered using Unity 5, which ran on an Intel Core i7-6700HQ CPU MSI laptop computer with 2.60 GHz core using an NVIDIA GeForce GTX 1060 graphics card. For the MitS display, we used the testbed settings created by the developers. A map

Figure 3. MitS display during route confirmation task.

Figure 4. Map display during route confirmation task.

was projected onto a virtual hemispheric dome with a radius of 1050 m using an orthographic projection centred at the participant's position. The self-marker was not presented directly above the participant at the centre of the dome, but rather at an offset such that the marker was presented at a 45° visual angle from the horizon, to make it easier for the user to see. The rest of the map was compressed to compensate for the offset, such that the map's projection was no longer orthographic (similar to dome with offset in Figure 2). The Map presentation showed the map tilted at a 30° angle. This was intended to simulate a smartphone or GPS device which is often held in front of the user at an angle.

An Oculus Rift Headset was used to display the virtual environment. The Rift has a 2160 × 1200 OLED display with a 110-degree field of view and 90 Hz refresh rate. Responses were made using an Oculus

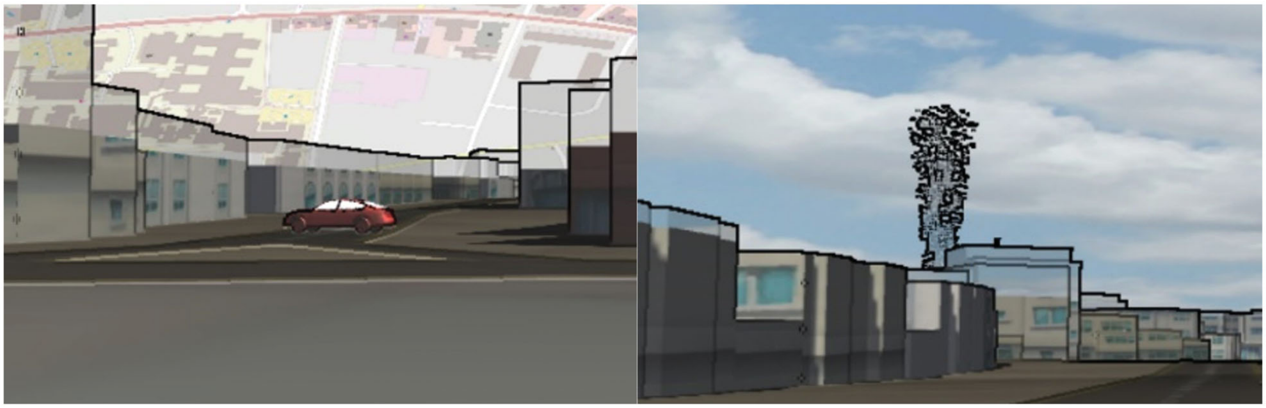

Figure 5. Target vehicle (left) and smoke column (right) threats.

Touch controller. The position of the headset and controller were tracked by two sensors located at opposite corners of the experimental room to track full 360-degree rotation. The participant viewed the route from a fixed starting position and could change the view on the environment by rotating the head or body. However, the participant could not locomote within the virtual environment (i.e. the participant could not leave the starting position).

A real-scale virtual environment was based on WRLD SDK for Unity (WRLD 3D, 2018) which provides a textured 3D environment based on the real world using a geographic coordinate system. Mapbox Maps SDK for Unity (Mapbox 2018), which uses the same geographic coordinate system, was used to present the maps. The use of a consistent coordinate system allowed selected latitude and longitude coordinates to specify the same area and match the virtual environment and the map in the displays. Both displays used the maps from the same online source, including the same features and colours, to preserve information equivalency.

We sought an urban area with a non-grid layout to produce scenes that were visually distinct and unpredictable in layout from trial to trial. To reduce occlusion of MitS, we also sought low building heights and wide roads. The real-world districts in and surrounding Brixton, South London, England met these criteria, and were available in WRLD SRK (between latitudes 51°28′29.6″N and 51°25′31.3″N and longitudes 0°09′08.6″W and 0°03′37.3″W, approximately 6.4 km by 5.5 km). All text and symbols were removed from the maps (eliminating the potential for reversed text and symbols in the MitS condition). The only additions were a red self-marker and a magenta line representing the proposed route (in both conditions).

For each trial, a route was created by randomly selecting a starting position within the boundaries defined above using latitude and longitude coordinates obtained from Google Maps. This point was adjusted to the closest intersection. The end of the route was then selected at a point exactly one kilometre away in a random direction, also adjusted to the closest intersection. If the point was near a boundary then only endpoints within the boundary could be chosen. A route was automatically generated using the shortest distance along streets between the two points, with at least one turn. Each route was displayed once to each participant.

Two types of threat were used in the experiment: a smoke column and a target vehicle (Figure 5). The smoke columns were shown using the particle system in Unity, such that a point emitted small particles that rose to approximately 100 m before disappearing, mimicking the movement of smoke. The 3D model for the target vehicle was obtained from the Unity library. Between one and three threats (at most two of each type), were randomly assigned to the 80 unique routes, with the constraint that half the routes were acceptable and half were not. Route acceptability was based on proximity to threats, where the route was classified as unacceptable if it passed within 10 m of a threat. All threat positions were adjusted to be visible from the starting point of the route.

Experimental design

The experiment had a 2×2 between/within design with Display as a within-subjects variable having two levels: MitS and Map, and VR Experience as the between-subjects variable. Participants sequentially completed two tasks on each trial: route confirmation and threat location. The experiment consisted of two blocks of 40 trials, one block with each display type. Block order was counterbalanced across participants.

Figure 6. Threat location window for MitS display.

Figure 7. Threat location window for Map display.

The *route confirmation* task asked participants whether a route presented in the display was safe to travel. The task placed the participant in the position of a soldier provided with a planned route in an urban environment. Reconnaissance has been done in the area, a route chosen, and the question is whether there are any current threats to traversal of the route. Recon has identified a red vehicle threat as a potential ambush or explosive device, and a smoke column represents a fire or explosion threat. The task was loosely based on an experiment designed by Ho et al. (2019).

To perform the task, participants had to detect the threats in the environment and relate the threat positions to the route shown on the MitS or Map display. This required visual inspection of the scene and an estimation of the threat's proximity to the route, by comparing the threat location in the scene to the route shown on the MitS or Map display.

For the *threat location* task, participants were shown a window with three possible threat location configurations (Figures 6 and 7) and were asked to select the option where the threats were located. The images were taken from screenshots of the same display format (MitS or Map) that the participant used in the trial. All three options used the same screenshot but overlaid different threat locations. The two distractor options could differ in two ways: the position and the number of threats. The position of the correct option in the display (i.e. first, second, or third) was randomly determined. The task was intended to represent the requirement to report threat locations after having left the environment (i.e. memory of the scene layout). The task was based on a retrospective spatial awareness task used by Hollands and Lamb (2011).

Our VR headset allowed measurement of participant head movements. We used these as rough indicators of gaze position, to examine information seeking behaviour in the route confirmation task. Two areas of interest were defined: the display and the environment (Figure 8). Ray casting was used to track the centre of participants' head position. For the current experiment, each intersection of the ray cast with a different area was classified as an *area-of-interest shift*, and the dwell duration after each shift was recorded. Duration was used to calculate percentage dwell time for the display and environment.

Procedure

Upon arriving at the experimental location, participants were asked to sign a consent form and complete a demographics questionnaire as well as the Santa Barbara Sense of Direction Scale (Hegarty et al. 2002), a well-known standardised measurement instrument to assess individual differences in spatial ability. Participants were shown a brief video explaining the purpose and mechanics of the experiment, including descriptions of the threats and criteria for a route being considered acceptable. Participants were told that, 'we are interested in both the speed and accuracy of your responses, so you should respond as quickly as you can, while also being as accurate as you can'. After the video, participants were fitted with the VR headset and took part in the experimental training.

Training consisted of 14 trials that gradually introduced various aspects of the experiment, including multiple examples of both threat types for acceptable and unacceptable routes. Trials with both the MitS and Map displays were presented and the experimenter provided participants with the correct answers for each task and threat distance. Participants were encouraged to ask questions during the training session, as the experimenter would not answer questions

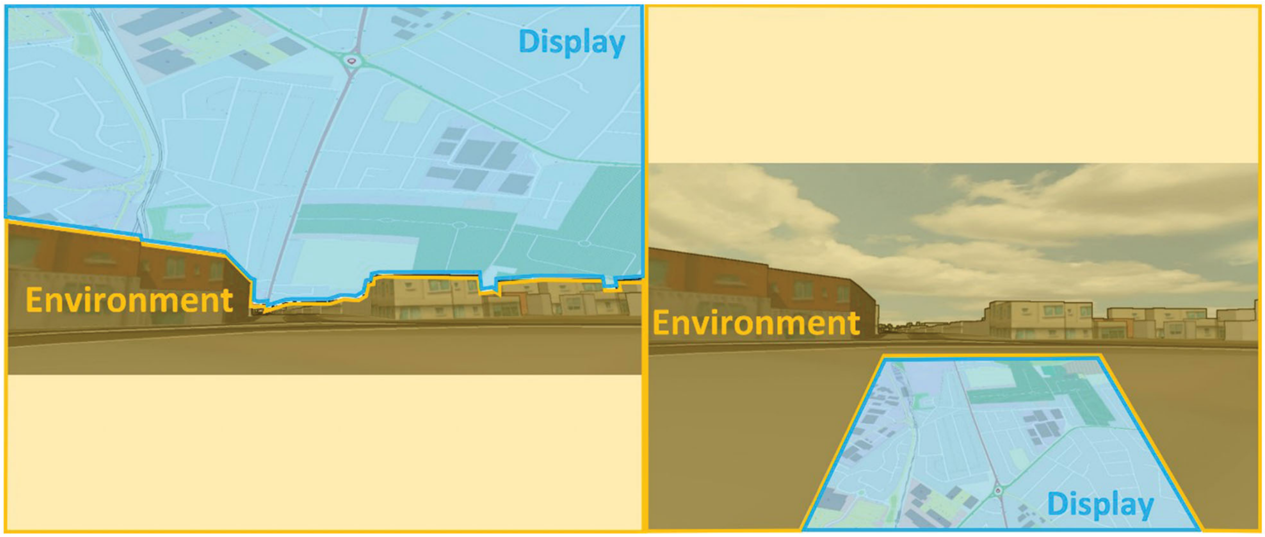

Figure 8. Area of interest definition with MitS (left) and the Map (right).

or provide feedback during the experimental trials. These trials were not timed and participants could take as long as they needed (generally between 60 and 90 s per trial). Participants were therefore exposed to MitS for only 10–15 min before beginning the experiment. A break was offered after the training block.

At the beginning of a trial, participants were shown a window that said, 'Get Ready'. Once the trial had loaded, the virtual environment was revealed. After 5 s, the prompt 'Is this route acceptable?' was shown, with the options 'Yes' and 'No' (e.g. Figure 3). After the participant responded, the environment was hidden and participants were shown the threat location task prompt, 'Where were the threats in the environment?' (e.g. Figure 6). Upon responding, the prompt disappeared and instructions were shown to press the trigger to start the next trial. No feedback was provided for either task. Each trial took about 45 s to complete.

At the halfway point and the end of each block, participants removed the headset to complete the NASA-TLX (Hart and Staveland 1988) and the System Acceptance Questionnaire (Van der Laan, Heino, and De Waard 1997), a commonly used tool designed to assess the perceived usefulness of and satisfaction with new technology, on a separate laptop. Participants were periodically offered breaks and told that if they felt unwell they could also take a break. Participants were informed that they could withdraw from the experiment at any time without penalty. After the final block, participants completed an exit questionnaire. This questionnaire asked participants to provide feedback about the experiment, including their strategy for performing the tasks, general throughts about the displays and MitS, whether they would consider using an AR version.

Results

The dependent variables for each task included accuracy, response time, and subjective workload. Accuracy was computed for each participant as the proportion of trials in which the participant correctly identified route acceptability and threat configuration for the route confirmation and threat location tasks, respectively. Response times were computed as the duration between the initial presentation of the environment and when a response was given for the route confirmation task, and duration between the initial appearance of the threat location window and a participant's response for the threat location task. Subjective workload was assessed using NASA-TLX. The System Acceptance Questionnaire collected participant feedback for the constructs of *usefulness* and *satisfaction*.

Each measure was subjected to a between/within analysis of variance (ANOVA) with VR Experience (Yes, No) and Display (MitS, Map) serving as independent variables. Planned comparisons were used to compare performance between Displays for each level of VR Experience. Results were considered significant at $p < .05$, and only significant effects are discussed below.

Route confirmation task

Route confirmation accuracy showed an interaction between Display and VR Experience, $F(1, 26) = 6.42$, $p = .0176$, $\eta_p^2 = .198$, $\eta_G^2 = .086$ (Figure 9). VR-

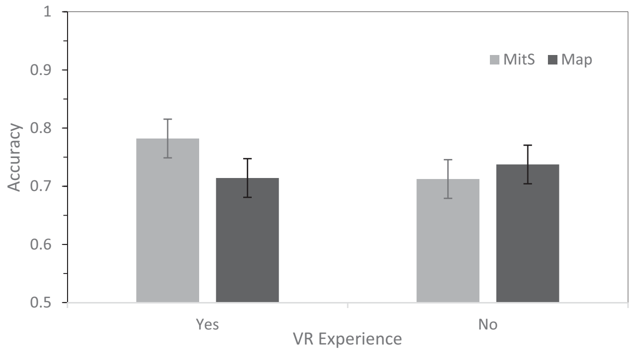

Figure 9. Accuracy by display and VR experience on route confirmation task. Error bars indicate 95% confidence interval in all graphs (Jarmasz and Hollands 2009).

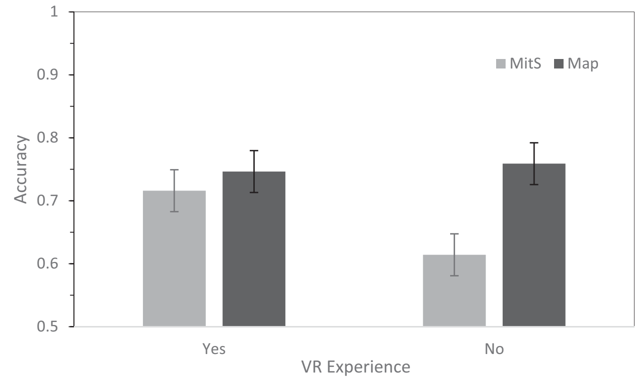

Figure 10. Accuracy by display and VR experience on threat location task.

experienced participants had a higher proportion of correct responses with MitS ($M = .782$) than the Map ($M = .714$), $t(13) = 3.06$, $p = .009$. There was no difference between display conditions for first-time VR users ($M_{MitS} = .713$, $M_{Map} = .738$), $t(13) = -.86$, $p > .05$. There were no significant effects for response time. Subjective workload showed a main effect for Display, $F(1,\ 26) = 6.29$, $p = .0187$, $\eta_p^2 = .195$, $\eta_G^2 = .084$. Participants produced a higher workload rating for MitS ($M = 4.71$) than the Map ($M = 4.35$).

Threat location task

For the threat location task, there was a main effect for Display on accuracy, $F(1,\ 26) = 14.65$, $p < .001$, $\eta_p^2 = .360$, $\eta_G^2 = .119$. Participants had a higher proportion of correct responses with the Map (M = .753) than with MitS (M = .665). There was also an interaction between Display and VR Experience, $F(1,\ 26) = 6.25$, $p = .0191$, $\eta_p^2 = .194$, $\eta_G^2 = .054$ (Figure 10). Whereas first-time VR users were less accurate with MitS (M = .614) than Map (M = .759), $t(13) = -4.22$, $p = .001$, there was no difference for VR-experienced participants, ($M_{MitS} = .716$, $M_{Map} = .746$), $t(13) = -1.00$, $p > .05$. There were main effects of Display for response time, $F(1,\ 26) = 5.19$, $p = .0312$, $\eta_p^2 = .166$, $\eta_G^2 = .071$, and subjective workload, $F(1,\ 26) = 19.65$, $p < .001$, $\eta_p^2 = .430$, $\eta_G^2 = .110$. Participants responded faster with the Map ($M = 7.26$ s) than with MitS ($M = 8.54$ s) and rated workload lower for the Map ($M = 4.27$) than MitS ($M = 4.75$).

For the System Acceptance Questionnaire, there was a main effect of Display on satisfaction, $F(1,\ 26) = 10.50$, $p = .003$, $\eta_p^2 = .288$, $\eta_G^2 = .083$, such that participants rated the Map ($M = .60$) higher than MitS ($M = .14$). There was also an effect of Display on usefulness, $F(1,\ 26) = 7.34$, $p = .0018$, $\eta_p^2 = .220$, $\eta_G^2 = .039$, where participants rated the Map ($M = .80$) higher than MitS ($M = .47$).

Information seeking behaviour

Using the head-tracking data, we recorded each time a ray cast from the headset intersected with a different area of interest during the route confirmation task. The number of area of interest shifts was computed for each participant in each condition. A main effect of Display was found, $F(1,\ 26) = 30.70$, $p < .001$, $\eta_p^2 = .541$, $\eta_G^2 = .371$. Participants made more area-of-interest shifts between MitS and the environment ($M = 14.21$) than between the Map and the environment ($M = 8.34$).

Duration data for 17 of 28 participants were lost, so we analysed the data from the remaining 11 participants for percentage dwell time. Percentage dwell time showed a main effect of Display, $F(1,\ 9) = 9.84$, $p = .012$, $\eta_p^2 = .522$, $\eta_G^2 = .394$. Participants spent a greater percentage of a trial dwelling on MitS ($M = .616$) than the Map ($M = .322$).

Discussion

In this study, performance with a novel mirror display format (MitS) was compared to a conventional electronic map display. Here, we summarise the results for each task and consider what may have led to them. Then we discuss the relationship between using VR for our experiment, the intended AR presentation of MitS, and the impact of display novelty on participants. Finally, we consider some limitations of our study and how they could be addressed in future work.

The tasks—inspired by military reconnaissance—required participants to confirm whether a route met certain criteria for safe passage, and to verify the correct location of threats near the route. The results show that although there was no difference in route confirmation performance between MitS and a track-up 2D Map for first-time VR users, MitS produced better performance than Map for VR-experienced participants. VR-experienced participants confirmed the viability of a route more accurately with MitS than with the Map. Nonetheless, MitS produced higher workload ratings for route confirmation than the Map.

For the threat location task, participants were required to select the alternative showing the correct threat locations in the trial. For this task, performance on all three primary dependent measures favoured the Map: participants were more accurate, had a lower response time, and lower subjective workload than with MitS.

We hypothesised that performance would be (i) better with MitS when required to relate information between the environment and display to make decisions; and (ii) better with the Map when remembering survey information. We also suggested that these results could be influenced by VR Experience. The first hypothesis was correct for accuracy with VR-experienced participants, though the results for subjective workload ran counter to the hypothesis. The second hypothesis was correct: the Map generally outperformed MitS on all dependent measures, although there was no Map-MitS accuracy difference for VR-experienced participants.

Display frame of reference comparison

The findings suggest that VR-experienced participants could perform the necessary cognitive translations required for the route confirmation task more accurately with MitS than the Map. The displays were informationally equivalent, using the same survey information, but MitS' presentation method may have led to higher computational efficiency for participants with prior VR experience. The accuracy advantage observed with MitS suggests that the reflection translation may exact less cognitive cost than the scaling translation required with the Map. As noted earlier, perceptual biases are commonly observed in VR studies, such as depth and slope underestimation. Such biases might have disproportionately affected distance judgements for first-time VR users with the real scale display of MitS relative to the 2D Map.

Participants made more area-of-interest shifts between the display and environment with MitS and spent a greater percentage of a trial looking at the MitS display than at the Map. Participants seemed to trade off the more physically demanding head movements when using the Map for increased working memory load, making fewer shifts and having a shorter percentage dwell time on the display compared to MitS. Using eye-tracking measures, Smith, Gabbard, and Conley (2016) found that their participants violated the NHTSA (2012) guideline for number of long glances (>2 s) with a HUD, and average glance duration was greater with the HUD than an HDD for a secondary task during a driving scenario. Smith et al. measured glance count in a different way (emphasizing 'long glances') and different context (driving). However, their results are similar to ours in that they also found a longer dwell time when the information was presented nearer to the FFOV. For our application, the long glances away from the environment would present less of a risk as the user can more easily stop to view a display when on foot than while driving.

The increased number of information seeking actions with MitS may reflect a lower IAC compared to the Map. Though MitS does not overlay information in the FFOV like a HUD, MitS is still generally closer to the FFOV than the Map. In the exit questionnaire, informal feedback suggested that MitS required 'less eye/head movement' and 'required less effort to orient'. Alternatively, the greater percentage dwell time with MitS may have been due to MitS's novelty, greater difficulty understanding reflected information, our definition of the areas of interest, or some combination of those factors.

Recalling survey information

For the threat location task, the cognitive translations required when using MitS appear to have provided less support for the user's spatial representation of the trial than the Map. With MitS, the left-right relationship when switching between the display and the environment is maintained, but the forward-backwards distance and height relative to the horizon are reversed (whereas both are maintained with the Map). As noted earlier, an object on the MitS display that is further from the horizon is closer to the user, but further from the actual object in the visual field. This difference may be easier to reconcile when viewing the display and environment at the same time but impaired when asked to recall threat positions with MitS only.

Performance on the threat location task would also be affected by the participant's cognitive representation of the scenario. If participants' cognitive representation of a trial is more world-centred, it might more closely correspond to the top-down Map presentation. In that case, selecting from options resembling that presentation should require less cognitive transformation (and therefore be more accurate).

Information seeking behaviour may have also influenced performance. Ishikawa and Takahashi (2014) found that participants showed poorer recognition of the environment in those conditions where they had spent more time looking at the display. This is similar to our finding that MitS produced a higher percentage dwell time than the Map, but poorer threat location recall afterwards. We further note that MitS produced a higher percentage dwell time than the Map without a difference in overall response time, which meant that participants spent less time attending to the environment with MitS. As such, participants may not have retained as much information about the threat locations compared to the Map.

Display and apparatus novelty

Considering that this experiment was our participants' first exposure to MitS, many were able to make use of the display and even outperform the Map's familiar display format. One participant stated in the exit questionnaire that, 'after some adjustment, I preferred the MitS display - didn't have to look at map, then back at route. It appeared more seamless'. The general novelty of both the VR apparatus and display may help to explain the effects of VR Experience. The conflicting sensory and motion cues experienced by first time VR users may have more negatively affected MitS than Map. It appears that as little as one or two sessions with VR may be sufficient to resolve some of the conflict between those cues.

With MitS, participants needed to estimate the distance of both the threats and the route for comparison, which may have increased the potential for errors if they had difficulty with perceiving distances in a virtual environment. In contrast, the route shown in the Map was presented close to the user in a familiar perspective.

The self-marker offset (implemented to provide users with more context of their surroundings without having to look directly up) may have been disorienting when rotating. Disorientation can contribute to simulator sickness, which can negatively impact performance and affect (Johnson 2005). It is possible that greater disorientation and its effects affected our first-time VR users more than those with VR experience.

Lack of familiarity may have contributed to increased workload and decreased satisfaction and usefulness ratings for MitS relative to Map. The higher subjective workload for MitS that occurred in both tasks may be partly attributable to its unfamiliarity. In the exit questionnaire, those participants favouring the Map condition explicitly noted its familiarity (e.g. 'it is similar to the map I am using on my phone, I am more used to it'). The higher satisfaction and usefulness ratings for the Map than MitS may have also been affected by familiarity, though those ratings for MitS were still positive.

Limitations and future research

For the threat location task, participants had to select one among three screenshots of the display. Other spatial memory recall tasks, such as virtual pointing or map drawing (e.g. Antrobus, Burnett, and Skrypchuk 2016; Gardony et al. 2013; Goldin and Thorndyke 1982) might have been used. However, these methods can be difficult to score, and would likely lengthen each trial.

The collection of measures of information seeking behaviour also had limitations. Head-tracking was used to determine which areas of interest participants dwelt on, although eye tracking would have been more precise. The granularity of our measure was therefore limited, although this was at least partially addressed by defining broad areas as environment and display. The broadly defined areas of interest could have had some inflation effect on the measures of number of area-shifts and/or percentage dwell time for MitS, since its display area was close to the horizon. Nonetheless, given that MitS produced almost double the area-shifts and percentage dwell time of the Map, we believe the conclusions drawn to be valid.

Using VR as a substitute for an AR display can have limitations, particularly with respect to the information content in virtual versus real environments. The virtual environment employed in the experiment did not contain objects like signs or garbage cans, which are plentiful in real environments. Ongoing research with MitS in our laboratory is including distractor objects in the virtual environment. Future research should investigate performance with AR presentations of MitS in real environments.

Only one set of display parameters (the developer-provided MitS v1.0 prototype with orthographic dome and position marker offset) was used for this study. Different parameters may have had different effects on performance. For example, relating the environment to the display might have been easier with a flatter projection. Future research planned with MitS will consider the effects of other projections and parameter values. We also plan to investigate performance on navigation tasks that include locomotion.

Conclusion

As AR technology improves, digital information in a variety of domains and applications will be integrated into user's everyday environments (Grier et al. 2012). In this article, we examined a promising AR application called MitS. We simulated a version of MitS in a virtual environment and compared performance using MitS and a 2D Map on route confirmation and threat location tasks. Participants with prior VR experience were found to have higher accuracy with MitS than the Map for route confirmation. However, performance related to recalling threat locations favoured the familiar Map over the unfamiliar MitS on multiple measures. Presenting survey information near the FFOV in navigation displays is currently uncommon, but our results suggest that future iterations of MitS might be a viable alternative to current maps, especially once projection and parameter values are validated through further experimentation with human users.

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