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ORIGINAL ARTICLE

Comparing handheld monoscopic and head-mounted stereoscopic optical see-through augmented reality indoor navigational aids across age and gender identity

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Abstract

Augmented reality (AR) systems are promising tools for navigation and wayfinding, but questions remain about optimal design and effectiveness. We developed an AR system to aid users' navigation through a complex building. We then explored three research questions. First, we asked how handheld monoscopic and head-mounted stereoscopic optical see-through AR tools affect a user's abilities to navigate an indoor environment for the first time, compared to a control group using no aid. We found that head-mounted stereoscopic optical see-through AR improved participants' abilities to navigate a novel environment, relative to the control group, but participants using handheld monoscopic AR performed worse than the control group. Second, we asked how AR changed users' abilities to navigate this indoor environment in future attempts without any technological assistance. When users were asked to navigate the environment for a second time, two weeks later, participants in all three groups significantly improved their performance. However, users in the control group improved the most. Third, we asked how improvements in navigational skill were related to users' age, gender identity, and spatial thinking skill. We found significant relationships between participants' age and navigational performance, and significant interactions between age and gender, but no relationship between spatial thinking ability and navigational performance. Within our sample ($n = 76$), we observed a clear benefit to using head-mounted stereoscopic optical see-through AR, but the handheld monoscopic AR hindered participants' ability to navigate the indoor environment for the first time.

Keywords Augmented reality · Navigation · Age · Gender · Monoscopic · Stereoscopic

1 Introduction

One of the most fundamental tasks in life is to navigate through space. Finding a destination is an essential human behavior, and spatial awareness is a necessary component of successful navigation activities (Montello 2005; Klippel et al. 2010). For millennia, humans have navigated using a combination of internal cues and external models/representations of the world (i.e., maps; Gladwin 1970; Warren 2001; Wolfe 2006; Aporta 2009; Clarke 2013). In recent decades, this has included highly interactive electronic navigational aids that incorporate other spatial technologies like global positioning systems (GPS) to locate a device's position. These maps and tools can make it easier to navigate a novel environment for the first time and help reduce cognitive load during wayfinding (Allen 1999; Brugger et al. 2019). They may also improve (or not improve) spatial learning about these environments, making it easier (or more difficult) to navigate the environment in future attempts without technological assistance. For example, research shows the use of GPS-enabled navigation while walking or driving can impair our ability to learn navigating new environments (Montello 2005; Gardony et al. 2013; Dahmani and Bohbot 2020). In other situations, navigational tools may improve spatial learning if they are able to sense specific behavioral patterns and direct the user's attention appropriately (Brugger et al. 2019). The general consensus among human spatial navigation researchers is that the change from static representations (i.e., maps) to interactive map displays (i.e., mobile GPS) influences the way we perceive,

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remember, and interact with our surrounding environment due the ability to access information at potentially any time or place. However, the type of influence is dependent on the type of technology and how information is communicated (Parush et al. 2007; Ishikawa et al. 2008; Klippel et al. 2010; Ishikawa and Takahashi 2013).

Although the effects of GPS on navigation and spatial learning are well known, there is less research on how augmented reality (AR) may affect navigation and spatial learning. AR is an emerging technology that people may use for navigating environments. Broadly defined, AR is any system that augments a space around the user by superimposing digital information using displays or optics to appear as if present in the real world. AR systems are a successor to wearable heads-up displays (HUDs); while both AR and HUDs superimpose digital information on a display or optics, HUDs do not include spatial registration that enables virtual content to be aligned with the user's surroundings. Types of three-dimensional displays have been used since the 1960's when they required entire rooms of equipment to power, but the ones in use today are compact enough to fit into a wearable headset not much larger than a pair of glasses (Sutherland 1968). Stereoscopic AR-enabled navigation is understudied, because the AR technology continues to evolve rapidly, but it is important to study because wearable AR technology is expected to compete with the handheld smartphone devices most people use today (Tran et al. 2023). AR-enabled navigation utilizes vision-based positioning (i.e. the use of built-in cameras to navigate), which provides the advantage of not relying on external sensors. AR navigation's use of vision-based positioning breaks away from traditional uses of AR as solely a visualization tool and positions AR as a spatial recognition tool that requires data capture and comparison to previously established 3D scans of environments (Niantic 2025). Vision-based positioning is considered a more modern technique with AR navigation compared to traditional satellite-based positioning (i.e. GPS) and companies in the private sector are developing new positioning systems using these technologies (Joshi et al. 2020). Google has already implemented AR navigation in select cities around the globe (Phillips 2023).

AR comes in three forms: optical see-through, video see-through, and projective see-through. Optical see-through and projective see-through utilize head-mounted displays (HMDs) that are typically visualized stereoscopically, and video see-through utilizes AR interfaces that are visualized monoscopically. This study focuses on comparing human perception of the technology during wayfinding and therefore subdivides AR into head-mounted stereoscopic optical see-through and handheld monoscopic AR. Stereoscopic optical see-through AR HMDs are devices worn on the user's head that utilize various types of optics to direct the light from digital images to a user's eyes and make it appear as if the digital object is located within the real world, depth perception included. Monoscopic HMDs exist, but they are typically classified as HUDs instead of AR. Monoscopic AR interfaces are typically handheld devices, usually smartphones, with a screen that displays the image produced by the device's camera and include localized digital information and objects overlayed onto the device's video feed. Research on AR increased significantly since 2010, with the increase in interest reflected almost entirely in mobile device applications (Cheliotis et al. 2023). The use of smartphones to visualize AR experiences is typically seen as a bridge to connect emerging AR glasses-style HMDs to consumers through the use of current technology they likely already own. While interest in handheld AR has increased dramatically, interest in the use of HMDs specifically for AR navigation has also seen a steady increase since 2019 (Cheliotis et al. 2023).

Previous research on the use of AR for navigation reveals the potential of this technology. Early work with mobile AR found that utilizing sparse localization with activity-based instructions along with both AR and non-AR information was effective in improving task performance when navigating an indoor environment (Mulloni et al. 2011). When comparing handheld AR devices and a wearable HUD, another study found that the wearable device was perceived to have higher navigational accuracy while the data indicated that navigational performance was not significantly different from the handheld device; both the handheld and wearable HUD navigational aids resulted in shorter navigation time and lower workload, but worse route retention compared to using paper maps (Rehman and Cao 2016). When comparing digital maps to handheld AR, one study found no significant differences between interface types regarding task completion time and distance traveled (Dünser et al. 2012). Many other studies have shown support for the use AR navigational aids compared to traditional wayfinding methods due to the reduced task completion times or fewer navigational errors (Rehman and Cao 2016; Smith et al. 2016; Rubio-Sandoval et al. 2021; Zhang et al. 2021). Given this body of research, it is clear that AR devices have the potential to be effective navigation tools. However, some studies have reported either no significant differences in AR vs. non-AR conditions or that a particular handheld AR navigational aid was inferior to mobile GPS (Rehrl et al. 2014; Dong et al. 2021; Lee 2022). AR shows great potential in many fields such as architecture, education, and navigation, but the mass adoption of the AR navigational aids will require perceived usability (the perception of the technology as being helpful for achieving goals effectively, efficiently, and enjoyably) and positive user experience (Davis 1989; Brooke 1996; Arifin et al. 2018; Dirin and Laine 2018).

Despite the demonstrated potential for AR devices to be effective navigation tools, there are challenges stemming from differences in performance among devices and among users. There is evidence that the effectiveness of mobile GPS and AR as navigational aids varies among users in both individual and systematic ways. Factors such as age, gender, navigation strategies, sense of direction, and spatial abilities affect wayfinding ability and performance, but there is little consensus in the literature regarding what factors have the greatest influence on wayfinding ability (Prestopnik 2000; Tahir and Krogstie 2023). Some people naturally learn spatial environments more quickly and efficiently than others (Ishikawa and Montello 2006), while others are incapable of daily spatial learning tasks without any observable medical condition (Iaria et al. 2009; Iaria and Barton 2010; Ekstrom et al. 2018). Declines in spatial ability are part of the natural aging process, with older adults reporting increased frequencies of getting lost and being less able to stay oriented, particularly in new environments (Burns 1999). Studies have shown greater navigational impairments in older adults compared to younger adults in both real-world (Wilkniss et al. 1997) and virtual environments (Moffat and Resnick 2002). While studying cognitive declines with aging has wide-ranging implications, the topic of gender in the field of navigation has also been discussed extensively over the years. Gender in navigation has been a recurring and sometimes controversial topic. Most gender studies within navigation suggest that men are better navigators than women (Astur et al. 1998, 2004; Cutmore et al. 2000; Malinowski and Gillespie 2001). However, other studies show that women have better memory than men for the position of objects in the absence of reference frames (Dahmani et al. 2023). Moreover, one study suggests that a concurrent and relevant stressor can motivate women to navigate comparably to men, potentially diminishing gender differences found within the navigation literature (Schinazi et al. 2023). When comparing digital maps to handheld AR interfaces, another study found that men outperformed women when using a digital map or AR interface with a map, but that women performed better with the handheld AR interface than with a digital map or AR interface with a map (Dünser et al. 2012).

For this research, we developed and evaluated an AR application for navigating an indoor environment. We explored three research questions. First, we asked how handheld monoscopic and head-mounted stereoscopic optical see-through AR tools affect participants' ability to navigate an indoor environment for the first time, compared to a control group using no aid. Second, we asked how AR will change users' abilities to navigate this indoor environment in future attempts. Third, we asked how improvements in navigational skill were related to users' age, gender identity, and spatial thinking skill.

- H1: AR will make it easier for users to navigate a novel environment, because it allows users to visualize the fastest path to a specified destination and works in a similar manner to other navigation apps people likely use while driving.
- H2: AR users' ability to navigate the environment on subsequent attempts will be similar to other technologies like mobile GPS (i.e., navigation would be faster), because of the reduced cognitive load when using navigational aids (Allen 1999; Brugger et al. 2019).
- H3: Spatial learning and improvements in navigational skill over time will be related to participants' age and spatial thinking ability, because of the natural deterioration of neural structures underlying spatial coding during aging (Colombo et al. 2017). We also hypothesized that men would outperform women due to the prevalence of that observation in the navigation literature.

2 Materials and methods

We developed the AR application using a game/physics engine to work on a variety of devices and operating systems. We then compared differences in navigational performance among three groups of participants: a group using our AR application on handheld monoscopic hardware (i.e., iPhone 15 Pro/iPad Pro running iOS), a second group using our AR application on head-mounted stereoscopic optical see-through hardware (i.e., the Magic Leap 2 AR glasses running Android), and a control group that did not use any AR device. These experimental groups were used to further understand the differences in navigational performance and spatial memory regarding age, gender identity, and spatial thinking ability.

2.1 Application development

Our application development utilized the C# programming language within Unity, a game engine created by Unity Technologies (San Francisco, CA) capable of managing the physics and spatial information collected by the user's device (Haas 2014). We developed the application to work on both iOS (iPhone 15 Pro /iPad Pro) and Android (Magic Leap 2) using the ARFoundation framework constructed from both Apple's ARKit and Android's ARCore libraries. We followed the design guidelines provided by Magic Leap for AR-specific content (Magic Leap 2023), and we further followed Jakob Nielsen's 10 Usability Heuristics for UI

Design (Nielsen 1994). UI elements were kept consistent across both devices used. Before the study was conducted, several rounds of heuristic review and beta testing were conducted to improve the usability of the developed application. Only one participant in the handheld monoscopic group utilized the iPad Pro because they found text on the iPhone 15 Pro to be too small to read.

To navigate using the application, users begin by scanning a QR code to assign their device's starting position based on the calculated offset from the QR code, and then select their destination from a dropdown menu. The local coordinates of each destination are pre-programmed into the application. Once a destination is selected, the application begins calculating the least-cost path between the device's current position and the selected destination using a pre-baked navigation mesh, which accounts for humanoid figure dimensions and environmental obstacles while only allowing a preset maximum slope between floor elevations. This least-cost path is visualized in the form of a line or track on the floor to follow. The visualization is akin to ones used in other popular GPS-assisted navigation applications on mobile devices such as Apple Maps and Google Maps where they display a point for the user's current location, a point for the selected destination, and a line overlayed onto a roadmap to follow.

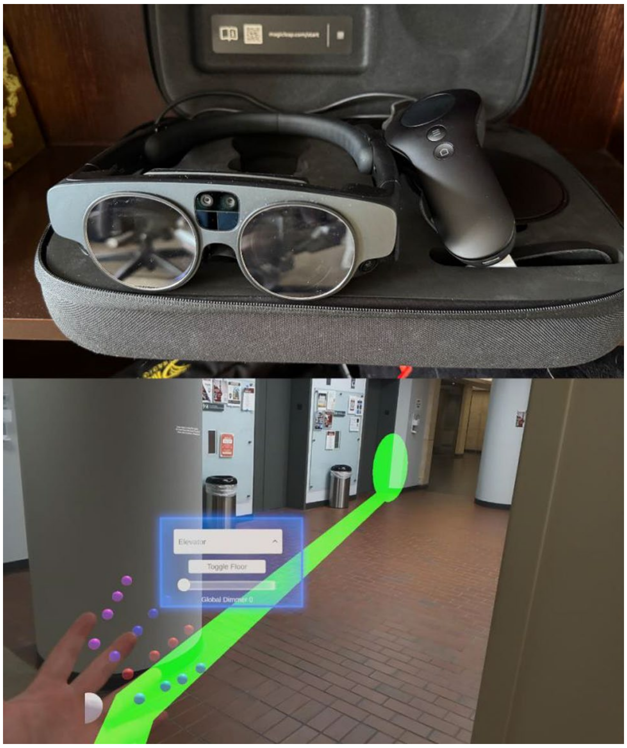


Fig. 1 Magic Leap 2 AR glasses (top) and a screenshot of a user's view while using the navigation tool implemented on a Magic Leap 2 device (bottom). The screenshot shows the hand-tracking interface to the navigation menu (colored dots), navigation target (green oval), and the path of travel recommended by the AR device (green line)

2.2 Hardware

There were two types of hardware used in this study: smartphones/tablets (iPhone 15 Pro/iPad Pro) and AR glasses (Magic Leap 2). When the application is running on the iOS devices, the spatial information is displayed monoscopically on the display as an overlay on the device's camera feed. When running on the AR glasses, the spatial information is displayed stereoscopically using waveguide optics that direct light through a transparent lens, giving users depth perception and the impression that the digital line and waypoints exist in the real-world space without obstructing the user's view. While the handheld monoscopic devices rely on touchscreen user interaction systems, the Magic Leap 2 AR glasses use a combination of handtracking and 6DoF controllers to operate. An example of what participants saw during the experiment can be found in Fig. 1.

There are several core components that work together inside a device to manage internal sensor data and apply desired actions to a virtual version of the space around the device. Almost all smartphones, tablets, and AR glasses utilize an inertial measurement unit (IMU), which consists of gyroscopes, accelerometers, and magnetometers to understand the physical movements of the device itself, but the devices can also be equipped with one or more cameras to interpret the world around the device (Yassin et al. 2016). These cameras can be supplemented with information from depth sensors, with light detection and ranging (LiDAR) being a common low-cost sensor option. This use of cameras to estimate changes in space for a physical device is commonly referred to as 'vision-based positioning' and has been a heavily researched topic with its applications growing in recent years (Morar et al. 2020). IMU's are prone to drift and electro-magnetic distortion issues, but the addition of cameras allows for correction and increases the robustness and accuracy of pose estimates (Schall et al. 2009). Some AR applications utilize GPS, which has inherent weaknesses within indoor environments, but one of the primary benefits of visual positioning systems (VPS) within indoor environments is the ability to position a device in real time without requiring any satellite connectivity (Kunhoth et al. 2020).

2.3 Experimental design

We wanted to see not only how the different AR technologies affect one's ability to navigate an indoor area relative to age, gender identity, and spatial thinking ability, but also how the different devices might affect their long-term spatial memory of that indoor environment when tasked with navigating without technological assistance. Participants were placed in groups and tasked with finding the same set of four randomly selected rooms, starting and ending in the same central location at the building's elevator bay. In spatial navigation studies, it is ideal to choose environments that are neither too simple nor too complex because normalization by having participants navigate many different environments is impractical (Ekstrom et al. 2018). The building we chose on the university's campus has a reputation for being challenging to navigate, and the semi-gridded layout and room numbering system doesn't follow an immediately identifiable pattern (Fig. 2). We isolated this study to the 2nd floor of this building because it has the most rooms and the largest available navigable area, and the use of technology that can partially obstruct the users view could pose a danger to participants when traversing obstacles like stairs.

We utilized a between-subjects design and created three experimental groups as follows: (1) A control group, who received no AR assistance, (2) A monoscopic group, who used a non-immersive 3D version of the application running on an iPhone 15 Pro or iPad Pro, and (3) A stereoscopic group, who used an immersive 3D version of the application running on the Magic Leap 2 AR glasses. Each experimental group was tasked with finding the same set of four rooms. The control group was given a list of rooms on paper and instructed to use any available visual cues to successfully complete the wayfinding task. The monoscopic and stereoscopic groups were given the same list of rooms inside the AR application and told to follow the visualized path to each room.

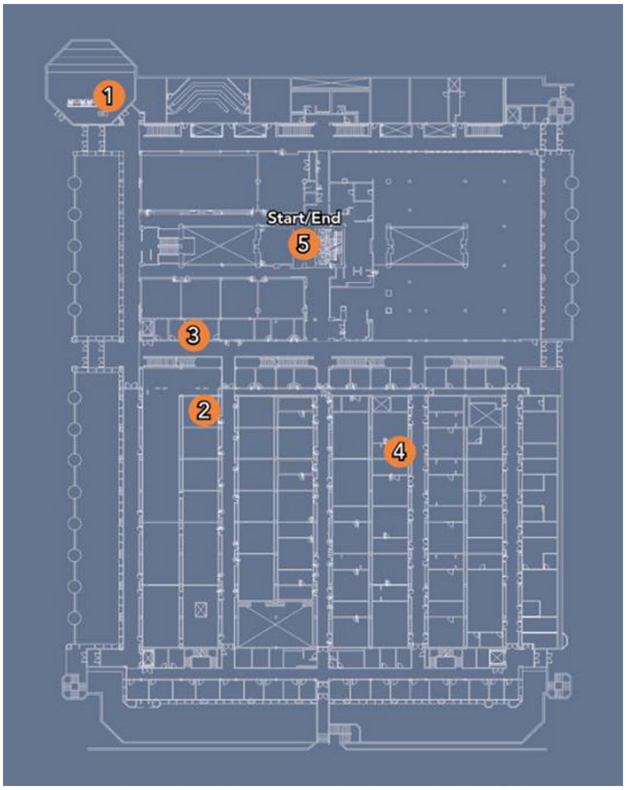


Fig. 2 Map of the study site with the numbers corresponding to the location of each target room and the order in which participants were tasked with finding them

We collected data on gender identity, age, and spatial thinking ability for the independent variables, with time traveled, distance traveled, and average walking speed as the dependent variables. The application recorded data on participants' time during the experiment as well as positional information every two seconds, which was used to calculate the Euclidean distance traveled. Once this initial task (Stage A) was completed, participants were asked to take a 16-question spatial thinking ability test (STAT), which represents extensive developmental work on the theoretical foundation of spatial thinking (Lee and Bednarz 2012). There are several spatial thinking components measured by STAT that can reflect one's natural ability to navigate, including map visualization and overlay, identification and classification of map symbols (point, line, area), generalized or abstract Boolean operations, map navigation or wayfinding, and recognition of positive spatial correlation. All participants were asked to return after two weeks to repeat the activity without any technological assistance to test how well the navigation task applied to their long-term spatial memory (Stage B).

2.4 Participants

Participants aged 18–60 were recruited via email and in person. To participate, volunteers were required to have no previous experience in the building nor with AR. Participants ages 18–30 were classified as young adults, while participants ages 31–60 were classified as middle-aged adults. The classification of young adults varies among human navigation studies with it most often being capped at 30, and people over the age of 60 are typically classified as older adults (Meneghetti et al. 2012; Yamamoto and DeGirolamo 2012; Korman et al. 2019; Merhav and Wolbers 2019; Hill et al. 2024). Middle-aged adults are often omitted from age-related navigation studies, but their inclusion can still offer insight into age-related navigational decline (Van der Ham and Claessen 2020). There were originally 90 people who participated in this experiment, which were randomly assigned to one of the three groups with a maximum of 30 per group. Some exceptions were made for the few participants who had pre-existing eye conditions that required the use of prescription lenses and prevented the use of AR glasses, and they were randomly assigned only to the control or handheld monoscopic groups so they could wear their prescription lenses during the experiment. Observations with incomplete survey or spatial data were removed, resulting in a final participant pool of 76.

2.5 Analyses

Several statistical tests were employed to investigate any potential relationships between the experimental groups' navigational performance and long-term spatial memory regarding distance, time, average walking speed, age, gender identity, and spatial thinking ability. However, walking speed was not included in every test due to its high accuracy in being used as an indicator for age (Pawlaczyk et al. 2021). First, we used one-way ANOVA to identify significant differences between the experimental groups regarding distance, time, and walking speed during Stage A alone. To test memory, we followed with paired sample t-tests to determine if there was a significant difference between participants' Stage A and Stage B with the distance and time traveled. We also performed one-way ANOVA with Tukey pairwise comparisons between the three groups regarding time and distance traveled to test for any significant differences between specific pairs. Additionally, we utilized interaction ANOVA to further understand potentially significant interactions between variables whose main effects were often significant by themselves. Spatial data collected by the application were also used to plot the location density of participants in each group to visualize latent variables that could potentially impact other variables like distance and time.

3 Results

This study recruited a total of 90 participants, with 30 for each technology condition. However, some participants blocked the device cameras at some point during the experiment, which caused a loss in positional tracking and resulted in inaccurate data. If a participant's device experienced tracking problems, it was evident when overlaid onto a map of the building. Participants' data were considered unreliable if their path passed through a wall at any point during the experiment. Any participant with unreliable positional data during either Stage A or B was removed before analysis, resulting in a total of 76 participants. The control group had the fewest number of participants ($n=21$). The handheld monoscopic group had the highest number of participants ($n=29$). The one participant was removed from the handheld monoscopic group was due to the app crashing mid-experiment. The head-mounted stereoscopic optical see-through group had 26 participants, fewer than the handheld monoscopic group, but more than the control group. Four participants had to be removed due to loss of tracking during the experiment, particularly in wide corridors with low-light conditions. Due to the study site being a university campus, most participants were classified as young adults ($n=59$), with fewer classified as middle-aged adults ($n=17$). The majority of the participants identified as male ($n=45$), with less than half the total number of participants identifying as female ($n=30$) and a single participant identifying as nonbinary/third gender. The distribution of gender identity across groups and age categories can be found in Tables 1 and 2.

Table 1 Distribution of participants' gender identity across experimental groups

Gender	CONTROL	MONO	STEREO	All groups
Male	8	21	16	45
Female	13	7	10	30
Nonbinary/third gender	0	1	0	1
All subjects	21	29	26	76

Table 2 Distribution of participants' gender identity across age groups

Gender	YA	MA	All groups
Male	37	8	45
Female	21	9	30
Nonbinary/third gender	1	0	1
All subjects	59	17	76

One-way ANOVA showed significant differences ($p=2.04e^{-08}$) among distance traveled between the control group (mean: 462.4 m, sd: 87 m), handheld monoscopic group (mean: 512.2 m; sd: 146.8 m), and head-mounted stereoscopic optical see-through group (mean: 319.5 m; sd: 65.5 m). One-way ANOVA also showed significant differences ($p<2e^{-16}$) with time traveled between the control group (mean: 486.9 s; sd: 117.3 s), handheld monoscopic group (mean: 610.4 s; sd: 46.7 s), and head-mounted stereoscopic optical see-through group (mean: 361.2 s; sd: 75.9 s). Additionally, one-way ANOVA showed significant differences ($p=0.04$) with average walking speed between the control group (mean: 0.97 m/s; sd: 0.17 m/s), handheld monoscopic group (mean: 0.84 m/s; 0.23 m/s), and head-mounted stereoscopic optical see-through group (mean: 0.89 m/s; sd: 0.1 m/s).

When users were asked to navigate the environment for a second time without technological assistance, two weeks later, participants in all three groups significantly improved their performance in terms of distance traveled (Fig. 3), time (Fig. 3) and speed (Fig. 4). However, users in the control group improved the most. The control group's paired sample t-test resulted in significant differences ($p<0.001$) with the change in distance traveled between Stage A (mean: 462.4 m; sd: 87 m) and Stage B (mean: 360.84 m; sd: 75 m). The handheld monoscopic group also resulted in significant differences ($p<0.001$) between Stage A (mean: 512.2 m; sd: 146.8 m) and Stage B (mean: 466.6 m; sd: 118.6 m). Similarly, the head-mounted stereoscopic optical see-through group also resulted in significant differences ($p<0.01$) between Stage A (mean: 319.5 m; sd: 65.5 m) and Stage B

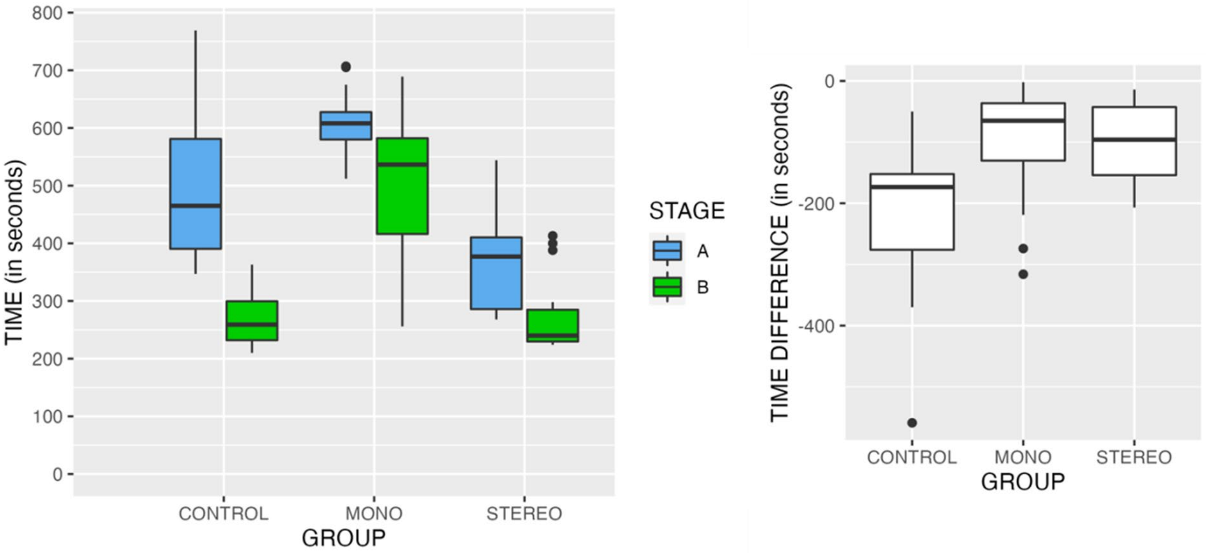


Fig. 3 (left) Boxplot of each group's total time traveled (in seconds) for Stage A (blue) and Stage B (green). (right) Boxplot of each group's difference in time traveled (in seconds) between stages

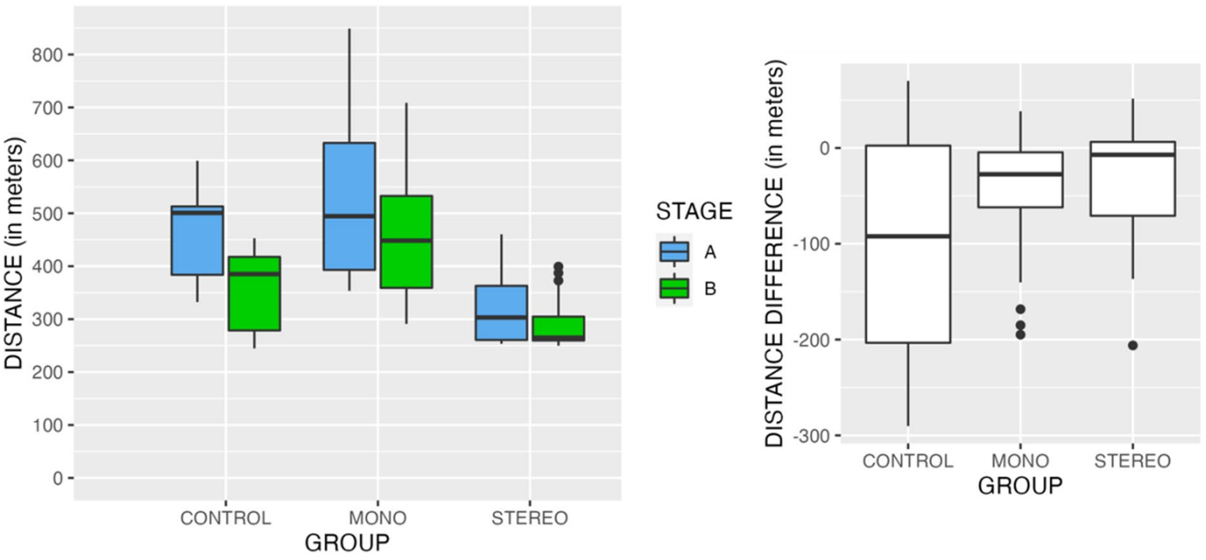


Fig. 4 (left) Boxplot of each group's Euclidean distance traveled (in meters) for Stage A (blue) and Stage B (green). (right) Boxplot of each group's difference in distance traveled (in meters) between stages

(mean: 287.2 m; sd: 44.9 m). One-way ANOVA resulted in significant differences ($p<0.01$) across all groups regarding the change in distance between stages. The Tukey pairwise comparison resulted in significant differences between the control and handheld monoscopic groups ($p=2.80\mathrm{e}^{-05}$), control and head-mounted stereoscopic optical see-through groups ($p<0.01$), but none between the handheld monoscopic and head-mounted stereoscopic optical see-through groups ($p=0.8$).

When assessing the amount of time that users took to complete the second navigation task, the control group's paired sample t-test resulted in significant differences ($p=2.74\mathrm{e}^{-08}$) with the change in time traveled between Stage A (mean: 486.9 s; sd: 117.3 s) and Stage B (mean: 268.6 s; sd: 45.7 s). The handheld monoscopic group also resulted in significant differences ($p=1.311\mathrm{e}^{-06}$) between Stage A (mean: 610.4 s; sd: 46.7 s) and Stage B (mean: 513.2 s; sd: 107 s). Similarly, the head-mounted stereoscopic optical see-through group also resulted in significant differences ($p=2.402\mathrm{e}^{-08}$) between Stage A (mean: 361.2 s; sd: 75.9 s) and Stage B (mean: 264.6 s; sd: 55.4 s). One-way ANOVA resulted in significant differences ($p=5.23\mathrm{e}^{-06}$) across all groups regarding the change in time between stages (Fig. 4). The Tukey pairwise comparison resulted in significant differences between the control and handheld monoscopic groups ($p=2.80\mathrm{e}^{-05}$), control and head-mounted stereoscopic optical see-through groups ($p=3.57\mathrm{e}^{-05}$), but none between the handheld monoscopic and head-mounted stereoscopic optical see-through groups ($p=1$).

Regarding walking speed during the second navigation task, the control group's paired sample t-test resulted in significant differences ($p=9.652\mathrm{e}^{-08}$) in the change in average walking speed between Stage A (mean: 0.97 m/s; sd: 0.17 m/s) and Stage B (mean: 1.35 m/s; sd: 0.21 m/s). The head-mounted stereoscopic optical see-through group also resulted in significant differences ($p=1.488\mathrm{e}^{-05}$) between Stage A (mean: 0.89 m/s; sd: 0.1 m/s) and Stage B (mean: 1.12 m/s; sd: 0.21 m/s). However, the handheld monoscopic group did not result in significant differences between Stage A (mean: 0.84 m/s; sd: 0.23 m/s) and Stage B (mean: 0.93 m/s; sd: 0.21 m/s). One-way ANOVA resulted in significant differences ($p=3.25\mathrm{e}^{-05}$) across all groups regarding the change in average walking speed between stages (Fig. 5). The Tukey pairwise comparison resulted in significant differences between the control and handheld monoscopic groups ($p<1\mathrm{e}^{-04}$), control and head-mounted stereoscopic optical see-through groups ($p=0.04$), and handheld monoscopic and head-mounted stereoscopic optical see-through groups ($p=0.05$).

We found significant relationships between participants' age and navigational performance, but no statistically significant relationship between spatial thinking ability and navigational performance. Here, we abbreviate young adults "YA" and middle-aged adults "MA". The interaction ANOVA did not result in a significant interaction between group and age regarding the distance difference between stages (Fig. 6). Note that negative values represent a reduction in distance or time traveled (i.e. improvement). Group showed a significant relationship with distance differences ($p=0.003$; control mean: −101.6 m; control sd: 107.5 m; monoscopic mean: −45.6 m; monoscopic sd: 62.6 m; stereoscopic mean: −2.2 m; stereoscopic sd: 58.9 m), and age resulted in significant differences ($p=0.002$; YA mean: −66.4 m; YA sd: 82.5 m; MA mean: −25.5 m; MA sd: 71.5), While the relationship between group and distance difference is significant, the interaction between group and age is not statistically significant ($p=0.06$) (Fig. 7). The interaction ANOVA did result in a significant interaction between group and age regarding the time difference between stages ($p=0.0004$). Age did not show a significant relationship with time difference ($p=0.84$; YA mean: −124.6 s; YA sd: 109.1 s; MA mean: −157.8 s; MA sd: 82.3 s), but group did show significance ($p=7.623\mathrm{e}^{-07}$; control mean: −218.3 s; control sd: 119.6 s; monoscopic mean: −97.2 s; monoscopic sd: 83.2 s; stereoscopic mean: −96.6 s; stereoscopic sd: 61.6 s). Spatial thinking ability showed no significant relationship ($p=0.87$) with distance differences, nor did it show any significant relationship ($p=0.09$) with time differences (Fig. 8).

We also found some significant effects related to gender identity. The one nonbinary participant was removed from this test due to the insufficient sample size. An interaction ANOVA did not show significant relationships between gender identity ($p=0.27$; male mean: −117 s; male sd: 88.9 s; female mean: −140.3 s; female sd: 96.6 s) or age ($p=0.14$; YA mean: −117.1 s; YA sd: 93.5 s; MA mean: −157.8 s; MA sd: 82.3 s) and the change in time between stages. However, there was a significant interaction between gender identity and age ($p=0.04$). When the interaction ANOVA was performed with the change in distance between stages,

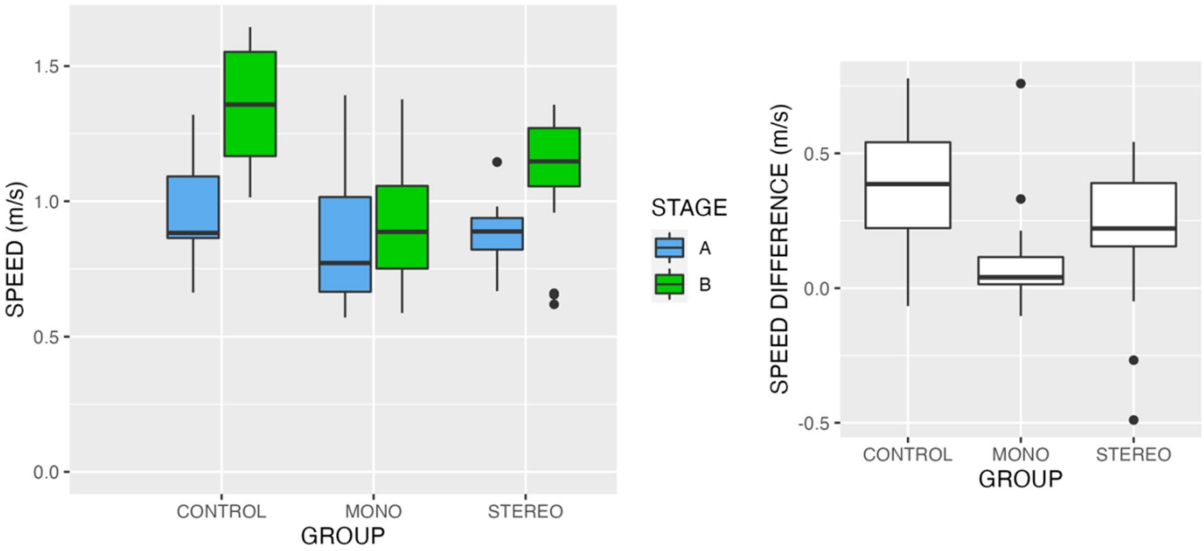


Fig. 5 (left) Boxplot of each group's average walking speed (m/s) for Stage A (blue) and Stage B (green). (right) Boxplot of each group's difference in average walking speed (m/s) between stages

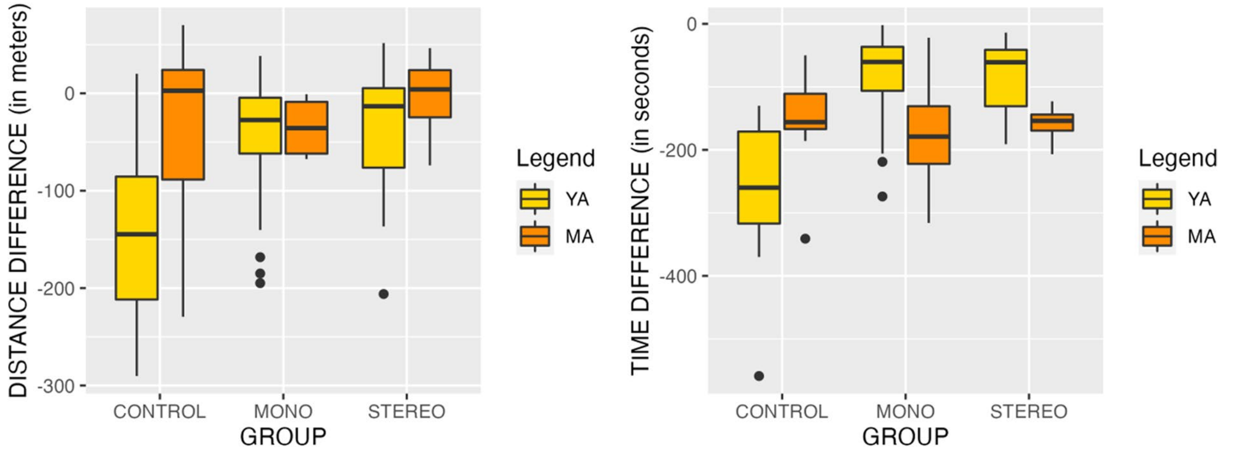


Fig. 6 (left) Boxplot of the difference in Euclidean distance traveled (in meters). (right) Boxplot of the difference in time traveled (in seconds) (y) between stages with young adults (YA-yellow) and middle-aged adults (MA-orange) across experimental groups

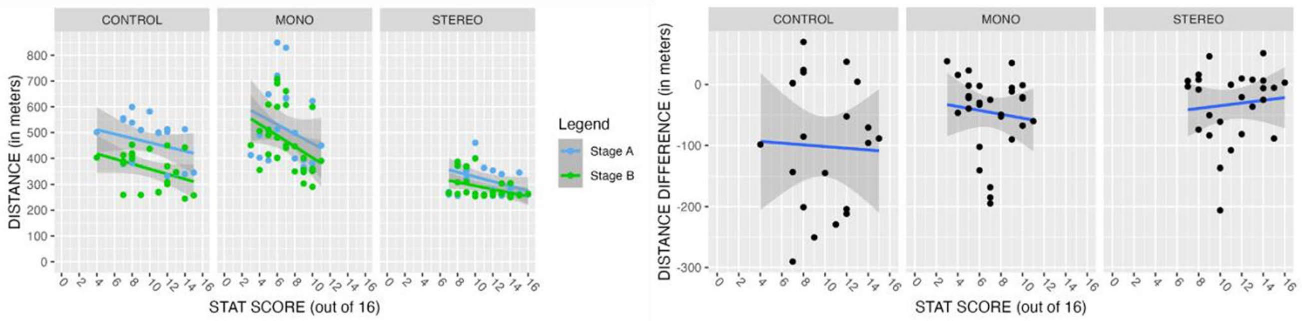


Fig. 7 (left) Linear regression of participants' spatial thinking ability score (x) and Euclidean distance traveled (in meters) (y) for Stage A (blue) and Stage B (green). (right) Linear regression of participants' spatial thinking ability score (x) and difference in Euclidean distance traveled (in meters) (y) between stages

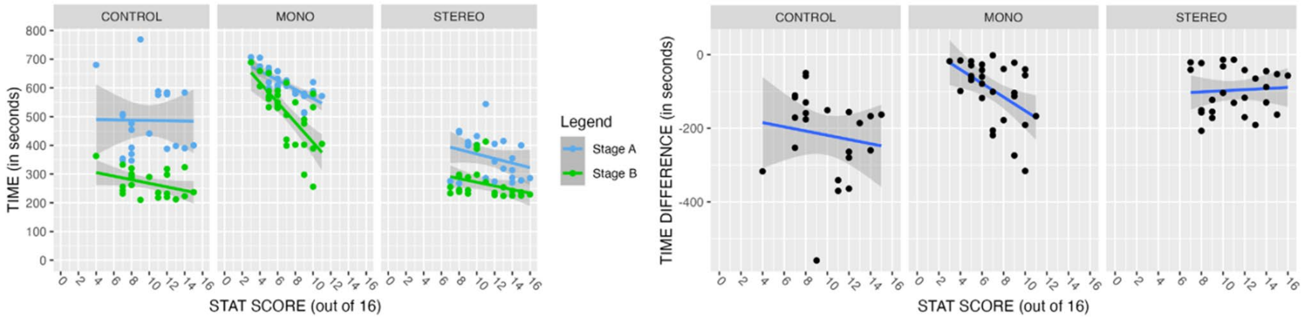


Fig. 8 (left) Linear regression of participants' spatial thinking ability score(x) and total time traveled (in seconds) (y) for Stage A (blue) and Stage B (green). (right) Linear regression of participants' spatial thinking ability score (x) and difference in time traveled (in seconds) (y) between stages

there was no significant relationship with gender identity (p=0.36; male mean: −48.2 m; male sd: 73.7 m; female mean: −64.4 m; female sd: 86.4 m) or age (p=0.05; YA mean: −63.2 m; YA sd: 79.5 m; MA mean: −25.5 m; MA sd: 71.5 m). Furthermore, there was a significant interaction between gender identity and age (p=0.02).

4 Discussion

On participants' first attempt, the head-mounted stereoscopic optical see-through group had the fastest times and shortest distances overall, while the handheld monoscopic group had the highest times and distances. These results are aligned with another study comparing the use of handheld monoscopic AR to the head-mounted stereoscopic optical see-through Microsoft HoloLens device when navigating two indoor environments (Bagling 2017). One possible explanation could be that displaying the information onto a small screen divided attention and hindered the effectiveness of the handheld monoscopic AR navigational aid and created added confusion, similar to observations in AR navigation driving studies (Bauerfeind et al. 2021, 2022). This lack of stereoscopic superimposition requires the user to map the AR information onto the real world in front of them similar to a heads-up display (HUD) (Pfannmuller 2017). Impacts of AR navigation on attention and awareness is currently an area of interest for researchers, with several studies focusing on developing and comparing different techniques for attention guiding (Renner and Pfeiffer 2017a, b; Renner and Pfeiffer 2020). Both devices used here utilized the exact same guiding system, therefor drawing concrete conclusions about attention guiding fall outside the scope of this study and we instead focus on comparing modes of visualization in handheld monoscopic AR to head-mounted stereoscopic optical see-through AR. A review of 184 experiments found that stereoscopic displays showed a clear benefit over monoscopic viewing in 65% of experiments that entailed finding objects, while only 25% of the experiments indicated no benefit (McIntire 2014). Our results are aligned with the majority of these similar studies comparing visualization methods.

Upon participants' second attempt navigating by memory alone, the trend from the first attempt continued with the head-mounted stereoscopic group performing the best while the handheld monoscopic group performed the worst. This means that the use of AR glasses helped participants remember the shortest route much better than the use of a handheld device. One explanation could be the divided attention between the handheld monoscopic device and the real world. Studies on the use of AR-enhanced windshields while driving resulted in both younger and older participants having significantly fewer navigation errors and divided attention-related issues when compared to using a regular monoscopic HUD due to its ability to facilitate glance behavior and reduce divided attention (Kim and Dey 2009; Gabbard et al. 2014; Bauerfeind et al. 2022). A study on head-mounted stereoscopic optical see-through AR navigation using a Microsoft HoloLens found that the AR device offered higher visibility to factors like oncoming traffic in the surrounding world, and EEG readings exposed a significantly less demanding focus level for the AR device compared to a smartphone (Guarese and Maciel 2019).

Walking speed without the context of differences between user interaction systems can be misleading. During Stage A, one would expect differences in walking speed between the three groups. Participants in the control group did not have to learn a new user interface (UI) and interaction system, resulting in more time and attention spent on their surrounding environment as well as more natural walking speeds. Participants in the handheld monoscopic group had the advantage of a familiar interaction system since they likely use touchscreens daily, but applying a 2D representation of a 3D space to the real world sometimes confused participants about where to turn and resulted in repeatedly alternating between looking at the device and the real world in front of them. None of the participants in the head-mounted stereoscopic optical see-through group had any previous experience combining handtracking and a 6DoF controller to interact with a UI that is tied to a virtual 3D space, resulting in more time spent at each waypoint attempting to select the correct next destination. Hesitation in navigation results in a clearly identifiable reduction of speed, and some types of UI have greater levels of automation and result in fewer hesitations or stops altogether (Brugger et al. 2019). If the time spent interacting with the application was recorded and subtracted from the numbers in the results, then the time spent traveling would have decreased and the average walking speed would have increased for the handheld monoscopic and head-mounted stereoscopic optical see-through groups during Stage A. Walking speed with AR navigation has not been extensively studied (Pawlaczyk et al. 2021; Ahn et al. 2024). Walking speed in a general situation is typically around 1.4 m/s, but one study observed an average walking speed of 1.08 m/s in participants within a maze-like structure, suggesting that corridor shape can have a great effect on walking speed (Lee et al. 2016). Furthermore, a recent study found that AR-assisted navigation led to a slight decrease in walking speed, but a significant reduction in the time required to restart navigation after encountering obstacles like stairs (Ahn et al. 2024). It is possible that the findings of this study are at least partially a result of the realized UI and not necessarily the selected hardware.

While distance traveled, time traveled, and average walking speed can be representative of this study's observations, there are variables that are best visualized using the recorded spatial data. Less time walking resulted in fewer recorded point data during the activity. Participants in the handheld monoscopic and head-mounted stereoscopic optical see-through group sometimes had to pause walking when interacting with the application to select their next destination. These pauses are apparent when the participants' chosen paths are overlayed onto the floor plan, displaying as hotspots at each of the destinations (Fig. 9). Across all groups, the head-mounted stereoscopic optical see-through group had the least visual variation between stages with the only hotspots at the areas of the floor they had to travel through more than once, which can be reflective of the aforementioned study (Ahn et al. 2024) due to participants having to restart navigation after arriving at each destination.

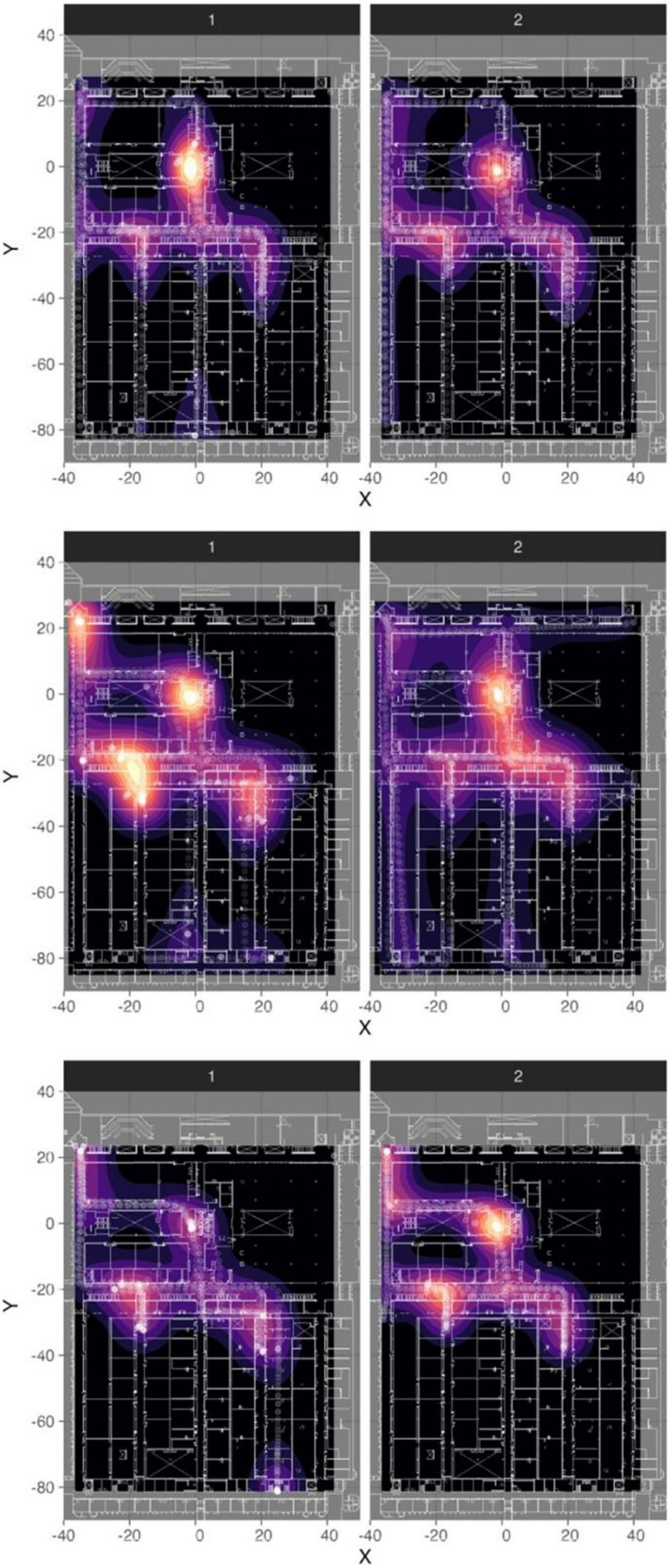
With the varying age ranges and categories found within the literature, directly comparing our results to many other studies on the effects of age in navigation presents a problem because few studies use the same age ranges for young and old adults, often omitting middle-aged adults altogether (Van der Ham abd Claessen 2020). In our results, there were clear differences between young and middle-aged adults regarding the change in distance between stages. The control group showed young adults having the best improvement in distance, which is reflective of other studies suggesting that spatial navigation and spatial memory performance decline with age (Van der Ham and Claessen 2020; Korman et al. 2019; Merhav and Wolbers 2019). The distance differences between age groups in the head-mounted stereoscopic optical see-through group were less pronounced than in the control group, and the distance differences between age groups in the handheld monoscopic group were miniscule. Interestingly, the middle-aged adults in the handheld monoscopic and head-mounted stereoscopic optical see-through groups actually showed better improvements than the young adults regarding the time spent traveling, suggesting that young adults exhibited lower confidence or capability in their navigation abilities when asked to complete the task two weeks later without assistance. Elements such as maps utilize a large amount of screen space on smartphones and can block the digital augmentation of the surrounding environment, which could potentially impact results and be a topic of future study. Adding another experimental group that is only shown a map either before or during the task like was done in Dünser et al. (2012) could add more insight to the effectiveness of different navigational technologies on people of different ages due to the suggestion that map reading skills do not have the same decline with age as is observed with exploratory navigation (Yamamoto and DeGirolamo 2012).

We did not find significant differences between men and women in general, but we did observe a clear difference when men and women were split within each age category. Most other studies found that men outperformed women in navigation tasks, but they were not split into the same age ranges that we used (Astur et al. 1998, 2004; Cutmore et al. 2000; Malinowski and Gillespie 2001). Younger women displayed better improvements in both time and distance compared to younger men, but middle-aged men displayed better improvements in both time and distance compared to middle-aged women. One of the primary motivations in other navigation investigations into gender differences is to attempt to understand factors that either influence or are influenced by women's predisposition to things like Alzheimer's disease, which manifests in the disease's early stages in the form of spatial disorientation, particularly in new environments but also sometimes familiar ones (Barnes et al. 2005; Hort et al. 2007; Kunz et al. 2015). Some areas of the brain related to spatial skills have also been observed deteriorating before the disease manifests and becomes diagnosable (Burggren et al. 2008; Braak et al. 2011). While medical research is not within the scope of this study, the differences of combined gender identity and age with navigational performance observed here could merit the inclusion of a middle-aged adult category into those studies that omitted them altogether to gain a better understanding of how soon and how fast those cognitive declines may appear within different demographic populations. Given that the navigational benefits of AR varied with users' age and gender identity, our study highlights the importance of assembling a diverse pool of test users when developing an AR navigation system.

While we initially recruited an equal number of participants to each experimental group, some participants were dropped from the analysis due to user error or technological problems (e.g., the application crashed). As a result, final sample sizes differed among our three experimental groups ($n=29$, 26, and 21 participants) and among gender identities ($n=45$ male, 30 female, and 1 nonbinary). Differences in sample size among groups can reduce statistical power and lead to Type I errors in ANOVA (Zar 1999). Type I errors occur when the null hypothesis is incorrectly rejected; thus, comparisons that resulted in a p-value slightly smaller than the typical cutoff of 0.05 have the highest potential for Type I error. While most of our p-values were several orders of magnitude smaller than 0.05, the significant differences among groups in average walking speed ($p=0.04$) and the significant interaction between gender and identity with the change in time between stages ($p=0.04$) are close to the threshold of non-significance and have the highest potential for Type I error. There also exists the potential for confounding effects due to inherent differences in the usability of the devices, including the different types of interaction systems (e.g. touchscreen vs. controllers vs. handtracking) and users' unfamiliarity with the controls. To minimize the potential for confounding effects due to differences in the usability the devices, we designed the application on both devices to utilize a single button interface, whether using touchscreen or handtracking with controller. It is also possible that limitations unique to each device influenced the results of this study. The Magic Leap 2 and Microsoft HoloLens 2 are both head-mounted stereoscopic optical see-through AR devices; however, the former's display field of view (FOV) is 45ºH x 55ºV (70ºD) and the latter's FOV is 43ºH x 29ºV (52ºD). Differences in FOV between these two devices may be a source of error in our results.

Our results overall have implications for both AR developers and future research. In applications where the primary

Fig. 9 Density plots of participant's recorded location every 2 s overlayed onto the floorplan in (top) the control group, (middle) the monoscopic group, and (bottom) the stereoscopic group



goal is for users to navigate a novel environment, our results suggest that head-mounted stereoscopic optical see-through AR may be more effective than handheld monoscopic AR. At the same time, handheld monoscopic AR devices are widely available (in the form of smartphones) and may offer the greatest prospects for widespread adoption (Cheliotis et al. 2023). Emerging research suggests that differences in performance among AR tools may be partly due attention-dividing between the AR device and the real-world environment (Bauerfeind et al. 2021, 2022). Thus, future research and development might focus on the development of AR tools that leverage the ubiquity of smartphones while mitigating challenges associated with attention-dividing between the device and environment (Renner and Pfeiffer 2017a, b; Renner and Pfeiffer 2020).

5 Conclusion

This study compared the performance of handheld monoscopic (smartphones) and head-mounted optical see-through (glasses) AR tools for navigating an indoor environment. Our first hypothesis was that AR would make it easier for users to navigate an environment for the first time. We found this to be true with the head-mounted stereoscopic optical see-through AR device, but not with handheld AR. Our second hypothesis was that subsequent attempts to navigate the same space would be faster for participants in the experimental AR groups. However, we found that the control group showed the greatest improvements in travel time. Our third hypothesis was that age, spatial thinking ability, and gender would impact navigational performance; while we did find a significant relationship between age and navigational performance, we did not find a relationship between spatial thinking ability and navigational performance, perhaps because our tasks involved route-following rather than map-based navigation. Thus, we conclude that head-mounted stereoscopic optical see-through AR navigational aids can reduce users' walking distance and travel time when navigating a novel indoor environment. If the ultimate goal is for users to learn to navigate the environment without assistance from an AR device, first-time navigation should be completed using head-mounted stereoscopic optical see-through AR or with no device.

Author contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by T.O.L. The first draft of the manuscript and figures were created by T.O.L. and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability Anonymized data and any scripts used during analysis are available upon request.

Declarations

Conflict of interest The authors declare no competing interests.

Ethical approval Ethical research permission was obtained by researchers from the Institutional Review Board at the University of Oklahoma, No. 14660.

Informed consent Informed consent was sought for all participants for participation in the project and for their de-identified data to be used for publication. The research was performed in accordance with the ethical standards as laid out in the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards.

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