Investigating the Effect of Visual Cue Density on Situational Awareness during Immersive Navigation

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Figure 1: In this work we explore the influence of visual navigation cue density on navigation performance, situational awareness and subjective user experience. The three investigated cues – (1) *PathLine*, (2) *ArrowTrail* and (3) *TurnMarker* – range from high to low density. To maintain experimental control and ensure a large-scale industrial environment, we conducted the study in Virtual Reality using a 3D scanned facility, where participants took the role of workers performing maintenance tasks.

Abstract

Navigation is a fundamental task supporting guided exploration and wayfinding as standalone or as part of other immersive applications. Previous research showed that navigational cues do not only impact wayfinding performance but can also affect perceptual and cognitive processes, e.g. divide attention and impair spatial memory. This study investigates whether varying the density of visual navigation cues can influence situational awareness. Additionally, we examine how cue density affects navigation usability and task performance. We compare three visual cue designs, ranging from high to low density: (1) *PathLine*, (2) *ArrowTrail* and (3) *TurnMarker*. We designed a user study augmenting a 3D scanned digital twin of a building with virtual machinery to simulate a factory floor maintenance task, where the cues guided participants to the next point of interest. A secondary task, the reporting of anomalies, was installed to assess situational awareness. Results showed that performance metrics remained unaffected by cue type, situational awareness and user experience results showed significant differences. Notably, the *ArrowTrail* cue, the medium-density design, was preferred by most participants and yielded the best overall results, e.g. in terms of anomaly detection and reaction time. These findings suggest that moderate cue density may offer an optimal balance between effective guidance and maintaining environmental awareness.

Index Terms: Virtual Reality, Augmented Reality, Guidance, Visual Cues, Navigation, Omnidirectional Treadmill

1 Introduction

Navigation is a fundamental aspect of human life, enabling us to move efficiently through our environment. For centuries, humans have developed tools and techniques to improve navigation, from celestial navigation and cartography to compasses and modern GPS systems. Today, navigation guidance is deeply integrated into our daily lives, whether through roadmaps, public transport systems, or digital assistants providing turn-by-turn directions.

New technologies, like Augmented Reality (AR), have introduced new opportunities to enhance navigation systems [12]. Optimized navigation is not only a topic in the physical world, but also in immersive Virtual Reality (VR) environments, that are used in gaming, training, simulation and industrial applications. Researchers explored guidance techniques to enhance wayfinding performance and also how navigation aids affect other important factors such as spatial memory, cognitive load, and the sense of immersion [59, 32, 39].

While navigation cues can improve task performance, they may also carry unintended consequences. For instance, visual cues can

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lead to reduced attention on uncued areas or affect spatial knowledge acquisition [15, 16, 20].

A decrease of Situational Awareness (SA) is especially relevant in AR scenarios, where cues are overlaid onto real-world environments and distractions can be a safety risk. This problem has motivated work, for example from Seeliger et al. [57], who proposed a machine learning-based system that selectively displays guidance cues to maintain safety and user awareness. However, their technique relies on a binary logic, by either showing the entire cue or hiding it completely. Motivated by this work, we want to explore whether adjusting the density of visual cues can affect SA. This could enable systems to move beyond the all-or-nothing paradigm and provide more nuanced, adaptive support based on context, and/or reflecting user preference or abilities.

We designed three types of navigation cues: *PathLine* (high density), *ArrowTrail* (medium density), and *TurnMarker* (low density). A study was conducted in a 3D scanned large-scale industrial environment in VR. An omnidirectional treadmill was used for locomotion for long distance natural walking behavior. In a simulated maintenance task, participants were asked to follow navigation cues to locate faulty machines while simultaneously reporting anomalies as a secondary task.

We evaluated each cue design on navigation performance, SA, and user experience. Navigation performance metrics remained unaffected by cue type, while SA related measures showed significant differences. Notably, *ArrowTrail*, the medium-density design, was preferred by participants and yielded the best overall results, e.g. in terms of anomaly detection and reaction time, while still being rated as supportive and easy to use.

2 Related Work

Our work was conducted in immersive VR to explore how navigation cues affect SA in a large, industrial environment. We include both VR and AR literature, as similar challenges arise in both. However, we do not claim the results to be directly transferable to AR or any other form of information presentation in the real-world, as this requires further experiments.

2.1 Effects of Visual Information Density

Visual density, defined as the number of visual elements or coverage per area [14, 65], affects how users attend to and process information. High visual density can lead to clutter, increasing visual information processing and impairing object detection [64, 63]. Research on visual saliency shows that attention is guided by both bottom-up (stimulus-driven) and top-down (task-driven) factors. Any change to the visual input (adding a navigation cue) alters the saliency map and consequently attention deployment [33, 69].

Navigation requires continuous integration of spatial knowledge (e.g., object relationships, self-motion) into a mental map [22, 7]. Hence, cue density, in modifying the deployment of attention might lead to over-reliance. This aligns with attention tunneling [71, 73], where over-reliance on a dominant cue monopolizes attentional resources, causing users to ignore critical environmental stimuli. In navigation tasks, attention tunneling has been shown to impair SA [1] and increase collision risks [30]. For instance, studies in HMD-based VR found that salient cues (e.g., flashing arrows) can suppress detection of peripheral obstacles [55].

2.2 Navigation and Guidance Cues

Navigation cues can be visual [24], auditory [36], or haptic [66] indicators designed to guide users or users' attention through environments, whether in AR, VR, video games, or other interactive systems. These cues help users reach destinations, find objects or complete tasks by providing directional or contextual guidance. The research covers several areas, from researching novel technical techniques [21] to investigating effects in mental load or spatial learning [74, 4].

Over time a variety of visual cues have been developed and investigated, each with different characteristics and suited for different scenarios. Some of these cues focus on guiding attention to objects or locations, particularly for short distances. For instance, the omnidirectional attention funnel [5] or similarly, the augmented tunnel by Hanson et al. [27] and Schwerdtfeger et al. [54]. Other types of cues, such as arrows, have been widely explored for guiding attention [6, 23, 46, 25, 31]. The Halo [3], which creates circles around off-screen targets, is similar to the Wedge [26], which uses triangles instead of circles to guide attention. A spherical wave-based guidance system is SWAVE [46]. The EyeSee360 [24], is a radar-like visualization, directing attention towards off-screen targets in 360° environments. Flickering-based cues [46]) or highlights [72, 45] are another technique for drawing attention to specific areas.

The mentioned cues are made to locate objects at short distances, e.g. to guide users' attention during 360° cinematic experiences [13, 28] or during assembly scenarios [45].

For long-distance scenarios other visual cues are suitable. Path-based cues are used in large scale environments and industrial settings [52, 47, 2, 57]. Also beacons and pointing arrows are investigated for guiding users across extended spaces [59, 8, 2]. Maps are another common solution for large environments, though they are more frequently used in urban or exploratory contexts [44, 75].

2.3 Potential Risks of Immersive Cues

Navigation or guidance cues have been widely explored for their ability to enhance wayfinding and task performance metrics [9, 34, 46, 56]. Beyond performance metrics, research has also explored perceptual and cognitive effects of such cues, like effects on SA, spatial memory or the users' sense of immersion in virtual environments [59, 32].

Persistent guidance cues can create visual clutter by overlapping with other elements, leading to distraction, attention tunneling, and spatial disorientation [2, 38, 41, 43]. Studies have shown that such cues may reduce attention and fixations on uncued areas [15, 16], limit natural visual scanning and eye accommodation [61, 42], and divert attentional resources away from the environment, potentially impairing SA and spatial memory [20]. This challenge is particularly relevant in AR scenarios, where virtual cues are overlaid onto real-world environments and users must stay aware of physical hazards. In industrial settings, for example, AR head-mounted displays have been shown to increase distraction and reduce SA [37], contribute to more safety incidents and missed hazards [10], and even delay responses to unexpected events due to added cognitive load [50]. These findings highlight a central trade-off in navigation design: enhancing guidance without compromising user safety.

Recent research increasingly focused on this safety challenge and explored solutions to reduce its impact [68, 60, 10, 50, 57]. For example, Su et al. [60] introduced obstacle reminders to help users avoid collisions, while Seeliger et al. [57] uses machine learning to selectively displays guidance cues to maintain safety and user awareness. However, their technique relies on a binary logic: either showing the entire cue or hiding it completely.

Similar concerns are addressed in VR research. Stefanucci et al. [59], investigated how navigational cues affect cognitive load and spatial learning in an VR environment. Jeong et al. [35] investigated how guidance cues and the users' cognitive load affect performance. VR offers greater experimental control and can be a useful tool for wayfinding studies [70]. It can also support the simulation of large-scale environments, making it well-suited for studying spatial knowledge acquisition and how it is affected by

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navigational cues [32, 19]. VR studies also investigate how navigational cues can influence the feeling of immersion [32, 39].

3 Objectives and Research Questions

The main objective of this study is to evaluate three different navigation cues with varying densities, assessing them in terms of:

Performance: We evaluate how accurately and quickly users can follow the navigation cues and complete the navigation task.

Situational Awareness: SA is described by Endsley and Garland [18] as the "perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future". We aim to measure how well participants maintain SA, in terms of identifying potential safety hazards or anomalies in the environment.

User Experience: We seek to understand how well participants feel supported by the cues and how easily they can understand and use them during the task.

Based on these objectives, we formulated the following research questions:

RQ1: Does the cue density impact the users' task performance?

RQ2: Does the cue density impact the users' ability to recognize anomalies in an industrial setting?

RQ3: Does the cue density impact the users' experience?

4 System Design

We conducted the study in a VR envrionment. We used a Meta Quest Pro headset[1] with integrated eye tracking capabilities in combination with the omnidirectional treadmill Omnideck[2]. The Omnideck enables unlimited physical walking within the virtual environment, providing a more natural locomotion within our simulated industrial scenario. Figure 1 shows a participant using the Omnideck.

4.1 Virtual Environment

The environment should closely resemble a real-world environment and offer a large area for exploration. To create the environment, a building floor (1243.8m^2) was scanned with a Matterport Pro3 camera (100 scan points). The longest straight walkable distance is 60m, Figure 2 shows the floor and one full path of 96.19m.

Added Machines: The scene was augmented with virtual machinery simulating a maintenance task for the study. The machines were visualized using a 3D model from the Unity Asset Store, provided by *CGY (Yemelyan K.)*[3]. This model was augmented with four interactive levers, each accompanied by an indicator light to signal the correct lever positions. When all levers are correctly aligned, the lights are green, signaling that the machine is functioning properly. Additionally, the screen of each machine is replaced with a stylized face, which displays a smiling expression when the machine is in good working order.

Anomalies were also placed along and outside the path, as described in Section 4.3. Figure 2 illustrates our experimental environment with added machines.

4.2 Navigation Cues

Our scenario is inspired by industrial use cases such as maintenance routes across large facilities, which is why we want to have a suitable navigation cue for long distances. The cues were intentionally designed to be simple and easy to interpret, with the goal of providing intuitive guidance without requiring additional explanation or training.

[1]https://www.meta.com/quest/quest-pro

[2]https://omnifinity.se/

[3]https://assetstore.unity.com/packages/3d/environments/sci-fi/atm-95057



Figure 2: We used a 3D scanned model of a buildings groundfloor (1243.8m^2), enriched with virtual laboratory equipment, as a base for our virtual environment. The groundfloor shows an example path of 96.19m and triangles indicate where the pictures below were taken.

In section 2 we mention several guidance and navigation cues, but not all of them are suitable for long distances.We decided to go for a path-based design, similar to Saha et al. [52], Renner and Pfeiffer [47], and Arntz et al. [2], as it is more fitted for longer distances and seems popular in industrial inspired scenarios.

In this study, we deliberately focused on cue density as the primary variable to investigate its impact on navigation and SA. While visual properties such as transparency or line thickness could also be important and worth exploring, introducing multiple parameters would have made it more difficult to control and interpret the effects of individual factors.

For our study we designed three different navigation cues, ranging from highest to lowest density: (1) *PathLine* (2) *ArrowTrail* and (3) *TurnMarker* (see Figure 3). Based on the concepts mentioned in section 2.1 we consider visual density in terms of the spatial frequency of the visualization.

PathLine highlights the whole path. This cue provides the highest density, using a continuous line along the path. We embedded directional indicators in the texture to guide the user as according to [47], path based visual cues should be augmented with directional information. *ArrowTrail* highlights the path every 2 meters and at corners. This is our medium-density design consisting of arrowheads placed every 2 meters and at corners along the route, offering periodic guidance without full path coverage. *TurnMarker* highlights only the corners of the path. This cue represents the lowest density design in our set. Inspired by hiking signs, it displays arrows only at key turning points, providing minimal guidance along the route. As this cue is very sparse we decided to use bigger arrows compared to *ArrowTrail* to make the cues easier to detect. All cues have a width of 0.7 meter and a transparency of 80%.

4.3 Anomalies

We introduced three types of anomalies (see Figure 4): (1) puddles, (2) loose cables and (3) abnormal machines. The abnormal machines differed from the standard machines, described in section 4.1, by the visualization on the screen. Instead of showing a

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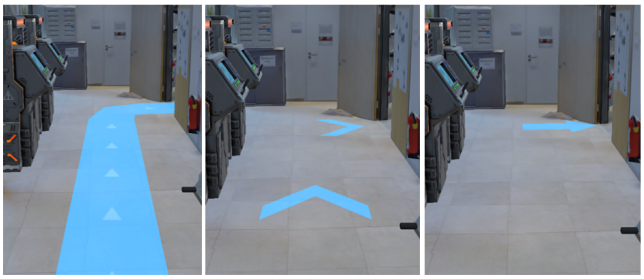


Figure 3: The pictures show the three cue designs, ranging from high to low density: (1) *PathLine*, (2) *ArrowTrail* and (3) *TurnMarker*.



Figure 4: To assess SA, we created 3 anomalies: puddles, loose cables and abnormal machines. During the study the participants need to report these anomalies while doing the main task.

smile, the expression shows a highly displeased expression. All other characteristics, like the lever position and lights, stayed the same. The abnormal machines do not interfere with the users main task in any way and they are not machines that need to be fixed.

These types of anomalies were chosen to maintain domain relevance: puddles, loose cables or abnormal looking machines could occur in an industrial environment. Also, the different types provide a variation in prominence and detectability: puddles and cables are typically floor-based, while abnormal machines are positioned around eye level, making them more prominent in the user's field of view. To add variety and avoid predictability, some puddles and cables were also placed on tables. Further details about anomaly placement are provided in section 5.4. In terms of visual characteristics, puddles are flat, low-contrast elements, making them subtler and potentially harder to notice. Cables are smaller and more compact, while abnormal machines show their irregularities more noticeable (on the screen). The abnormal machines are placed among normal machines, requiring users to recognize inconsistencies on the machines' screens.

5 Study Design

The working assumption of this work is that navigation cue density has a effect on SA. The study was designed using a dual task format to quantify navigation performance together with SA based on identifying objects in the scene while navigating. The study consists of three conditions, one for each navigation cue.

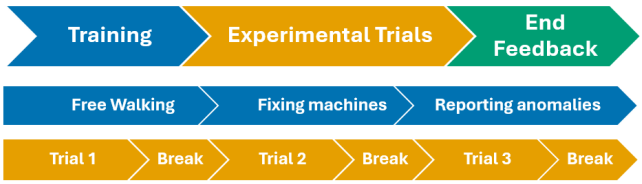


Figure 5: Before starting the trials for each cue, participants had to complete a training. In this training users were introduced to the omnideck, the virtual environment and to the required interactions. After the training, the main part of the study started where participants completed three trails, one for each cue. In the breaks between the trials, users could rest and fill out questionnaires. In the end a questionnaire was given to capture feedback and preferences.

5.1 Participants

Prior to the main study, a pilot test was conducted with three individuals to refine the procedure and ensure technical feasibility. A total of 24 participants (10 female, 14 male) voluntarily took part in the study. The mean age was 32.3 years, with ages ranging from 23 to 48 years. All participants reported normal or corrected-to-normal vision. Five participants had prior experience using the omnidirectional treadmill, for the remaining participants, this was their first exposure to the device. The study was conducted in accordance with the ethics guidelines of our institution, and all participants provided written informed consent prior to participation.

5.2 Procedure

To test and evaluate our navigation cue designs, we conducted a user study using a within-subjects design, allowing all participants to experience each of the three cue types. We counterbalanced the order of cue conditions so that each cue appeared equally often in the first, second, and third position across participants.

Figure 5 illustrates the overall structure of the study. Following a brief introduction to the study goals and procedures, participants completed a structured training phase divided into three parts: (a) Omnideck training, (b) machine interaction training, and (c) anomaly reporting training.

In phase (a), participants familiarized themselves with the Omnideck treadmill and the virtual environment used throughout the study. By using the same environment for training and the main trials, we aimed to reduce distraction due to environmental novelty. Participants were encouraged to explore all areas of the scene—not only to practice walking on the treadmill but also to build spatial familiarity. This phase was untimed, and progression was based on the mutual agreement of the participant and study supervisor that the user was confident and ready to proceed.

Phase (b) introduced participants to the virtual machines and the interaction required to "fix" them. Broken machines were distributed across the environment, and participants practiced visiting and repairing them. While the interaction itself was kept simple (see Section 5.3 for details), this phase ensured sufficient practice, particularly in combination with treadmill walking.

In phase (c), participants were trained to recognize and report anomalies. All three anomaly types were demonstrated within the scene, showing how they might appear during the main trials. To complete this phase, users had to successfully locate and report all anomalies. We placed 4 anomalies of each type in the training.

During the training, the Omnideck speed was adjusted to match individual preferences. All participants began at a default speed of 40%, which was then fine-tuned based on user feedback (mean = 49.5, SD = 6.3). During the main study, no adjustments were taken to ensure a fair comparison between cues.

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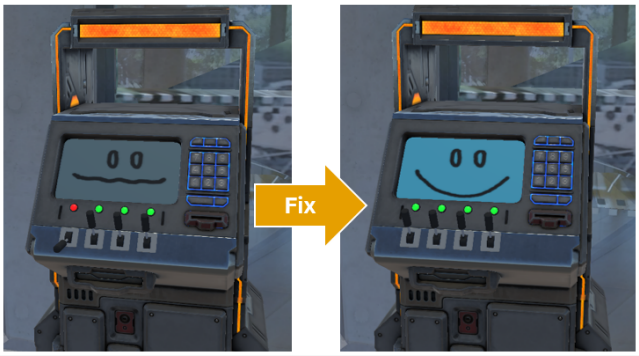


Figure 6: For the main task, users had to follow the navigation cues and fix faulty machines. A faulty machine was indicated by one red control light and a displeased facial expression on the screen. Machines could be repaired by adjusting the faulty lever until all lights turned green and the machine's facial expression returned to a smile.

After training, participants proceeded with the actual experimental phase. Short breaks were provided between trials to prevent fatigue and to allow participants to complete questionnaires. During these breaks, the VR headset was removed, and paper-based questionnaires were administered. These included: The NASA-TLX [29] to measure perceived workload and a customized usability questionnaire inspired by Arntz et al. [2], assessing perceived support and ease of use.

After completing all three trials, participants were given a final questionnaire designed to capture subjective feedback, personal preferences, and overall impressions of the navigation cue designs.

5.3 Tasks

The task was inspired by maintenance workflows in an industrial factory setting, where workers must navigate large spaces, perform equipment checks, and remain aware of potential safety hazards. In each trial, participants received instructions from a virtual panel displayed at the beginning of the scenario. The instructions remained consistent across all three trials.

Main Task: The main task involved locating and "fixing" malfunctioning machines placed throughout the environment. The machines were added to the environment as described in section 4.1. The machine model was augmented with four interactive levers, each accompanied by an indicator light to signal the correct lever positions. When all levers were correctly aligned, the lights turned green, signaling that the machine was functioning properly. Additionally, the screen of each machine was replaced with a stylized face, which displayed a smiling expression when the machine was in good working order. In contrast, malfunctioning or maintenance-needing machines displayed a neutral or displeased expression. The indicator lights served to guide users by highlighting which specific levers were incorrectly positioned. Machines could be repaired by adjusting the faulty lever until all lights turned green and the machine's facial expression returned to a satisfied smile (see Figure 6). Navigation cues guided participants from one faulty machine to the next, with the cue only updating once the current machine was successfully repaired. In each trial, participants had to *repair* 18 machines. Participants were instructed to focus primarily on their main task: following the navigation cues and repairing malfunctioning machines. While the environment allowed for free exploration and did not constrain users to a fixed path, participants were explicitly asked not to deviate from the route.

Secondary Task: While performing the main task, participants were also given a secondary task: to report anomalies encountered along the way. Thanks to the eye-tracking capabilities of the VR headset, anomalies could be reported by simply looking at them and pressing a button on the controller. Participants were instructed not to search for anomalies actively but to report them only when noticed during the course of their main task.

Although instructions emphasized passive observation, it is possible that individual differences in cautiousness or task engagement led some participants to actively scan the environment more thoroughly than others. This behavior may have introduced a bias in anomaly reporting performance, which could be addressed or controlled more systematically in future work.

Participants were also asked to report each anomaly only once. However, if they were unsure whether they had already reported a specific anomaly, they were encouraged to report it again to avoid missing any. With this we wanted to investigate if participants can remember already visited rooms and anomalies, which could indicate effects on spatial memory. However, we intentionally formulated this request softly, as our main focus in this work is SA. There were 18 anomalies in each path (6 cables, 6 puddles, 6 abnormal machines). Anomalies could emerge or disappear after completing some specified segment. The next section 5.4 clarifies details about the anomaly placement.

5.4 Path Construction and Anomaly Placement

Since all participants experienced all cue types, it was necessary to design three different paths that were both, varied enough to prevent participants from becoming familiar with the route, yet similar enough to remain comparable. The same applies for the placement of anomalies: ensuring variability, while maintaining comparability. In the following we will describe in more detail how we designed the paths and placed the anomalies.

Path Design: To achieve the balance mentioned above, we implemented the following design strategy:

The factory floor was divided into three sections, and each path began in one of these sections (Path 1 starting in Section A, Path 2 in Section B, and Path 3 in Section C). Figure 2 shows the floorplan divided into 3 sections.

Each path was constructed by selecting machines in a logical order, ensuring that participants would navigate through the environment in a structured sequence. For each path, the goal was to visit machines in each area, and after traversing the floor once, the route reversed, revisiting all areas and returning to the starting point. During the first traversal, three machines from each area were visited. During the second traversal, two machines from each area were visited. In addition to the 15 machines within the areas, participants also encountered 3 machines in the hallway that connected the areas. These hallway machines were placed at the start (as the first machine to visit), in the middle (before the second traversal), and at the end (as the final machine visited). In total, participants would visit 18 machines, covering a total route length of 398 meters. To ensure that the paths were varied but still comparable, we selected machines in close proximity within each area, while reversing their order of visitation across different paths. For instance, in Area B, Path 1 may visit machines A and C, while Path 2 could visit machines B (near A) and D (near C), but in the order D-A. In the second traversal, the machines would be visited in a different order (e.g., A-D for Path 1 and C-A for Path 2).

This approach ensured that participants followed distinct paths without becoming overly familiar with the sequence, while maintaining comparability between the different cue designs.

Anomalies: Anomaly placement followed the same guiding principles: ensuring variability across the three paths to prevent learning effects, while maintaining comparability. The type of anomalies are mentioned in section 4.3.

Each anomaly type (puddle, cable, abnormal machine) was represented 6 times per path, resulting in a total of 18 anomalies per trial. The characteristics, spatial distribution, and visibility timing

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of anomalies were matched across all three paths to ensure consistency in difficulty and detection opportunity. As an example we want to explain the placement of the 6 puddles: Puddle 1, was visible only at the first traversal, placed near a machine in one of the main areas, while Puddle 2 was only visible at the second traversal in the same area as puddle 1. Puddle 3 and 4 were placed in both traversals in the hallway, located on the left and right side of the path. Puddle 5 was placed on a table within one of the areas, while Puddle 6 was located centrally (not close to any object) in an open space in one of the areas. The placement of cables and abnormal machines followed a similar system.

5.5 Collected Data

During each condition, we collected data on participants' performance in the navigation and anomaly-reporting tasks, alongside measures related to perceived support, usability, and cognitive workload.

Performance: To assess the overall performance across different cue designs, we evaluated participants' navigation task execution. We continuously recorded participants' positions during the trials, along with key events such as the start of the task (after reading the introduction panel), the completion of each machine interaction, and the final task completion (last machine fixed). From this data, we calculated both total completion time and distance traveled as indicators of task performance.

SA: User awareness was assessed through the secondary task of anomaly reporting. To evaluate report performance, we analyzed the number of anomalies reported, the frequency of duplicate reports, and the reaction times between first visual exposure and report. Data on each report was collected, complemented by eye-tracking data from the Meta Quest Pro headset, which allowed us to calculate reaction times for anomaly detection and reporting.

Subjective Measures To understand participants' perceptions of the cues, we collected subjective measures of support, ease of use, and workload. A custom 7-point Likert-scale questionnaire (ranging from "strongly disagree" to "strongly agree") was developed to assess perceived support and usability of each cue type. In these questionnaires participant had to rate statements like "I felt confident following this cue without needing additional help" and "I immediately understood what this cue was instructing me to do". In total there were 8 statements (4 for support, 4 for ease of use) they had to rate. In addition, the NASA Task Load Index (NASA-TLX) [29] was used to measure overall perceived workload during each condition.

6 Results

In this section, we present the findings of our user study. We begin with the results related to navigation performance, followed by the analysis of SA, and conclude with the measures regarding usability and user preferences. Given our within-subjects design, where all participants experienced each cue condition, we employed the Friedman test to determine whether there were statistically significant differences across cue types. This non-parametric test is well-suited for repeated-measures designs, especially when assumptions of normality may not hold [62]. In cases where the Friedman test indicated significant effects, we conducted Nemenyi post hoc comparisons to identify which specific cue conditions significantly differed from one another. Effect sizes were calculated with Kendall's W (W). Since multiple tests were conducted to evaluate awareness-related measures, we corrected the p-values using the False Discovery Rate FDR procedure.

6.1 Performance

To assess the performance of the cues and address **RQ1**, we measured both the time participants required to complete the main task

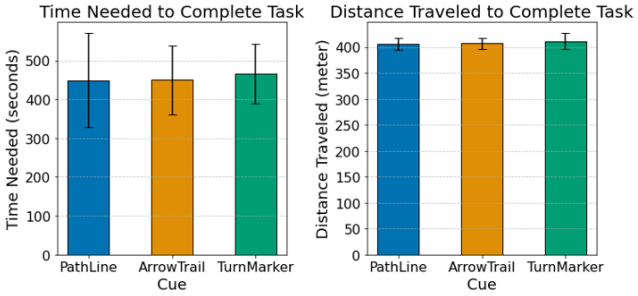


Figure 7: The plots visualize the average time needed and distance traveled to complete the task. No significant differences were found.

	p-value	adjusted p
Reported Anomalies	0.836	0.9218
Reported Puddles	0.0034	0.0103
Reported Anomalies (1st visit)	0.059	0.1194
Reaction Time Reports	0.0019	0.0103
Multiple reported Anomalies	0.8464	0.9218
Multiple Reports Count	0.9218	0.9218

Table 1: We did multiple tests to assess the performance of the report task. we corrected the p-values with the FDR approach.

of fixing all the machines and the total distance they traveled during the task.

There were no significant differences in either the time needed (p = 0.2748, χ^2 = 2.58, W = 0.2748) or the distance traveled (p = 0.4169, χ^2 = 1.75, W = 0.036) across the different cue types, suggesting that the variation in cue density did not have a substantial impact on task performance. Figure 7 shows the average completion time and distance traveled for each cue.

6.2 Situational Awareness

We decided to measure SA by performance measures. They occur naturally within the flow of the task and serve as indirect indicators of SA [53]. In more detail, we are assessing the performance of the secondary task: the reporting of anomalies. To evaluate the report performance we look at different metrics, all listed in table 1, e.g. the amount of found anomalies or the reaction time of reports. As we did several tests for the report performance, we adjusted the p-values with the FDR approach.

Overall there was clearly no significant difference in the total amount of found and reported anomalies (p = 0.836/0.9218, χ^2 = 0.36, W = 0.0.007). During the study we recognized that the puddles were in general more difficult to detect for the users, that is why we decided to also check for reported puddles separately. Here the results showed a significant difference, also after FDR correction (p = 0.0034/0.0103, χ^2 = 11.34, W = 0.236). The post-hoc test revealed that *PathLine* had significant less reports in puddles than *ArrowTrail* and *TurnMarker*. The result is visualized in Figure 8.

As the environment is traversed two times, there are some anomalies that are passed by more than once, resulting in the change to report it multiple times, this is why we also checked for the reported anomalies after one visit. Although the result indicates more difference here it is still not significant (p = 0.0.059/0.1194, χ^2 = 5.64, W = 0.11).

As we were able to gather eye tracking data from the participants we were interested in how long it took them from first seeing the anomaly, to actually reporting it. As the 'first seen' timestamp we only considered occurrences with a minimum gaze dwell time of 150ms and within 60 seconds before the report to reduce the

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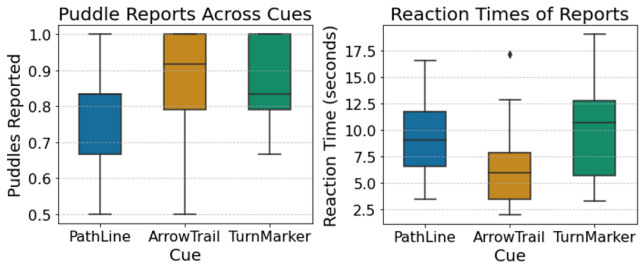


Figure 8: The count of puddle reports were significantly lower for *PathLine*, while the total count of reports showed no significance. *ArrowTrail* showed the best result for report reaction times.

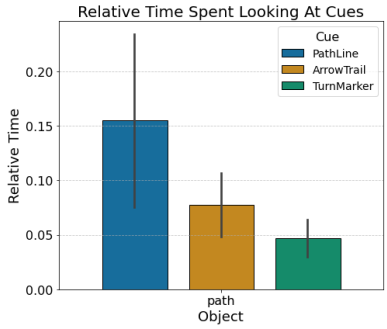


Figure 9: The plot shows the amount of time spent on looking at the cues, relative to the total time needed to finish the task.

risk of some outliers influencing the result, e.g. caused by inaccurate long distance eye tracking. Figure 8 shows the distribution of the reaction times over cues. To use the Friedman test we calculated the mean reaction time for each participant and cue. Results showed that there is a significant difference (p = 0.0019/0.0103, χ^2 = 12.58, W = 0.262). The post-hoc test revealed that *ArrowTrail* had significant better results in reaction time than the other two cues (p = 0.0025, p = 0.0167), while there was no significant difference between *PathLine* and *TurnMarker* (p = 0.8322).

We also checked if anomalies were seen and not reported. But this appeared not to be the case for all participants.

We also analyzed multiple reports. In the instructions we stated that anomalies should only be reported once, but in case of uncertainty, they could report them multiple times. The underlying idea was to assess if the users understood their environment and recognized that they were already in this room and reported the anomaly. Results here show that there was no significance difference in the amount of anomalies that were reported (p = 0.8464/0.0921, χ^2 = 0.33, W = 0.007) and also in the amount of 'extra' reports (p = 0.9218/0.9218, χ^2 = 0.16, W = 0.003).

Beyond report behavior, we also examined gaze behavior toward navigation cues. We calculated the percentage of time participants spent looking at the path in relation to their total task completion time. Results indicated a significant difference between cue conditions ($p < 0.05$). Results of all three conditions differed significantly with participants spending more time looking at the *PathLine* cue, followed by the *ArrowTrail* and *TurnMarker* cue. While this outcome may be expected, given that higher density cues occupy more space, it reinforces the concern that high-density cues may visually dominate the scene, potentially distracting users or occluding important environmental elements. See Figure 9 for a summary of time spent looking on the path across cues.

6.3 Usability / Subjective Measures

To assess user experience, we created a customized Likert questionnaire aimed at evaluating the perceived support and ease of use of the navigation cues. We also made use of the NASA TLX [29] to assess participants' workload. After each condition users had time for a break and to fill out the questionnaires.

6.3.1 Perceived Support and Ease of Use

In the subjective experience (**RQ3**) questionnaire, participants rated 8 statements after each condition (4 about perceived support and 4 about ease of use). Statements were, for example "I felt confident following this cue without needing additional help" and "I immediately understood what this cue was instructing me to do".

There are significant differences for both support ($p < 0.05$, χ^2 = 34,95, W = 0.728) and ease of use ($p < 0.05$, χ^2 = 27.44, W = 0.572). The post-hoc test indicated that, in terms of perceived support, *TurnMarker* was significantly less effective than both *PathLine* and *ArrowTrail* ($p < 0.05$ and $p < 0.05$). There was no significant difference between *PathLine* and *ArrowTrail* ($p < 0.05$). Regarding ease of use, *TurnMarker* was also rated lower than the other two cues ($p < 0.05$, $p < 0.05$), while no significant difference was observed between *PathLine* and *ArrowTrail* ($p < 0.05$).

6.3.2 NASA TLX

In addition to assessing the perceived support and ease of use, we also evaluated the participants' workload using the NASA TLX questionnaire. We calculate the RTLX score as an average of its subscales as suggested by Hart [29]. We excluded the temporal dimension of the NASA TLX from the analysis, as it was not applicable to our study context. The average results for each dimension are visualized in figure 10.

There was a significant difference in workload (p = 0.0147, χ^2 = 8.43, W = 0.176) between the different cue types. The post-hoc test indicated that *TurnMarker* resulted in a significantly higher workload compared to both *PathLine* (p = 0.0167) and *ArrowTrail* (p = 0.1072), the difference between *PathLine* and *ArrowTrail* was not significant (p = 0.7506).

6.3.3 Participant Feedback

At the end of the study, participants completed a final feedback questionnaire. We asked them to indicate which cue they found most helpful, which one required the least effort to use, and which one was their overall favorite. While 16 of participants rated *PathLine* as the most helpful and even 20 as the easiest to use, 15 out of 24 participants ultimately selected *ArrowTrail* as their overall favorite. Participants explained that *ArrowTrail* remained easy to understand while feeling less restrictive and visually intrusive, allowing them to see more of the environment. Interestingly, no one selected *TurnMarker* as favorite. However, several acknowledged that once they understood how it functioned, appearing only when a direction change was required, it became easier to follow. Figure 11 summarizes outcomes on preference across all cue types. 3 participants voted for multiple cues in each category, e.g. one user mentioned all 3 cues in the LeastEffort category.

Participants were also asked whether they believed the navigation cues influenced their attention. 22 out of 24 acknowledged that the cues could indeed impact their SA. They cited distraction due to an overload of information with *PathLine*, and a lack of support with *TurnMarker*. Additionally, 15 participants reported that following *TurnMarker* demanded more mental effort, which may have diverted their attention from the surrounding environment. This is also underlined by the results of the NASA TLX results (see section 6.3.2). Only 7 participants mentioned that they think that *PathLine* had a negative influence on their SA, 3 people even assumed it would improve their SA by providing so much navigational support that they could focus more on the environment.

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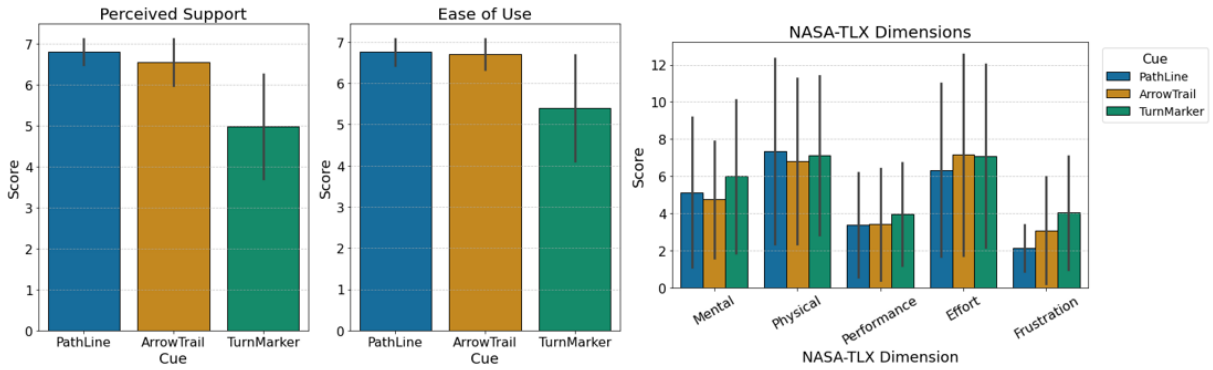


Figure 10: These plots show the results of the subjective user experience. *TurnMarker* scored significantly lower in perceived support and ease of use. Also the Nasa TLX indicates a significant higher workload for *TurnMarker* compared to the other cues.

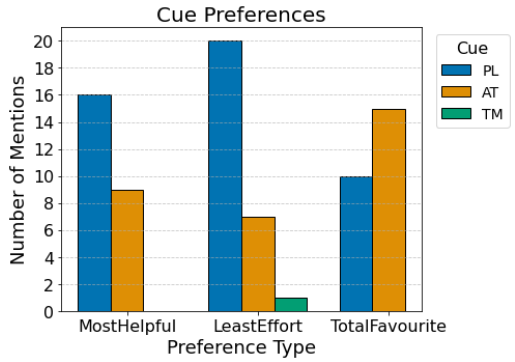


Figure 11: Most participants rated *PathLine* as the most helpful and easiest to understand. However, when asked about their overall preference, the majority still chose *ArrowTrail*. In their explanations, they appreciated that it provided sufficient guidance while being less visually intrusive. For them, it offered a more comfortable balance between perceived support and visual distraction.

7 Discussion

Based on the comparison between the cues, we analyzed the data to investigate their impact on *Navigation Performance* (**RQ1**), *Awareness* (**RQ2**) and *User Experience* (**RQ3**).

To answer **RQ1** and assess *Navigation Performance*, we investigated task completion time and travel distance. For completion time, we initially hypothesized that *ArrowTrail* would lead to the most efficient performance, as we thought users would need more time to interpret *TurnMarker* and follow *PathLine* more strictly, possibly leading to longer distance traveled and time needed. The data did not support this assumption. Notably, the effect size for the time needed was small to moderate, suggesting a possible trend that our study may have been underpowered to detect a potential Type II error. Future studies with larger samples or more complex spatial layouts may be better positioned to detect an effect.

We hypothesized that, in affording greater freedom in navigation, *TurnMarker* would lead to shorter travel distances, similar to the findings of Arntz et al. [2]. However, the data revealed no significant difference. It is possible that the constrained layout of our environment and the chosen path design (with a limited amount of open areas) limited participants' ability to take alternative paths, reducing the potential impact of this cue type on navigation behavior.

To assess *SA* and answer **RQ2** we evaluated participants' performance on a secondary task: the reporting of anomalies during navigation. Although the cues are kept simple and appear to be similar, their impact on SA was notable. *TurnMarker*, which was the most visually distinct, did not significantly differ from *PathLine* in secondary task performance. However, *ArrowTrail* led to significantly better results, suggesting improved SA. While the total number of reported anomalies did not significantly vary across cue conditions, detection of more subtle anomalies, such as puddles, was influenced by cue type. The result for reported puddles showed a small-to-moderate effect. Although the effect might not be large it can still be meaningful, especially as our used anomalies did not differ much in detectability.

Reaction times for reporting anomalies differed significantly, with *ArrowTrail* leading to the quickest responses. The effect size suggests a moderate effect, indicating that cue design had a meaningful impact on participants' ability to respond promptly to recognized anomalies. These findings align with prior research suggesting that persistent navigational cues can divide attention and reduce fixations on non-cued areas [15, 16, 20]. *PathLine* may have divided users' attention more strongly due to its higher spatial frequency. *TurnMarker* also led to low awareness performance, possibly because its sparse design distracted users in a different way by requiring them to search for the next cue. These results correspond with the feedback of participants, mentioning that *PathLine* felt too intrusive and *TurnMarker* required more mental effort to follow.

We examined multiple anomaly reports, in an attempt to asses spatial memory, but we observed no significant differences between cue conditions. While this result might suggest that cue design did not influence spatial knowledge, we acknowledge that our study design was not optimized to robustly assess this metric. Participants were instructed to report each anomaly only once, but in case of uncertainty they could report them multiple times. We intentionally formulated this instruction softly which may have introduced inconsistencies in behavior. Prior work has employed more targeted approaches to assess spatial memory, such as requiring participants to point or go back to specific locations [59]. Therefore, we advise caution in interpreting these results and suggest that future research employ more specialized methods to investigate this aspect of navigation behavior.

Overall, the results suggest that even subtle differences in cue design can influence SA.

To assess **RQ3**, we examined users' experience and preferences. Two customized questionnaires were developed to evaluate the perceived support and ease of use of each cue. Results indicated no significant difference between *PathLine* and *ArrowTrail* in terms of perceived support and ease of use. *TurnMarker* received significantly lower ratings on both dimensions. The effect sizes for these comparisons were notably high, indicating a strong influence of cue

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type on user experience. Compared to the smaller effect sizes observed for performance and awareness-related outcomes, these findings represent the most pronounced differences in the study. This suggests that, regardless of objective performance, users formed clear and consistent preferences regarding which cues they found most supportive and intuitive to use.

These subjective impressions were further supported by the NASA TLX results, which showed a significantly higher perceived workload for the *TurnMarker* condition, while no significant differences were found between *PathLine* and *ArrowTrail*. We assumed that a decrease in cue density would lead to an increase in perceived workload, as spotting the cues require more mental effort. As expected, *TurnMarker*, offering the least cue density, resulted in the highest workload scores. However, *ArrowTrail*, having a medium level of cue density, did not differ significantly from *PathLine*, which offers the highest density of guidance. This result suggests that reducing cue density moderately (*ArrowTrail*) may not negatively impact workload, while a more drastic reduction (*TurnMarker*) does.

In a final feedback questionnaire, participants were also asked about their overall preferences. While many acknowledged that *PathLine* was the most helpful and required the least effort to interpret and follow, the majority still preferred *ArrowTrail*. Participants justified their preference by noting that *ArrowTrail* felt less restrictive, less visually intrusive, and less distracting, while still offering sufficient navigational support. This discrepancy suggests that participants prioritized a balance between navigational support and visual comfort. Although *PathLine* minimized subjective cognitive effort, it may have introduced a feeling of overreliance or visual clutter. These subjective preferences align with the awareness-related results, where *ArrowTrail* also led to quicker anomaly detection, suggesting that moderate cue density can improve both user satisfaction and SA performance. These findings point to the importance of designing navigation aids that are supportive in navigation but minimally intrusive. Another interesting observation is that only 7 participants reported believing that *PathLine* had a negative impact on their SA, while 3 even assumed it would improve their SA by reducing cognitive effort. However, both *PathLine* and *TurnMarker* resulted in worse SA-related performance compared to *ArrowTrail*. Despite this, the majority of participants attributed potential negative effects on SA primarily to *TurnMarker*. This discrepancy suggests a possible risk of underestimating the attentional costs of visually dominant cues. Since *PathLine* highlights the whole path and is easy to follow, it may subtly draw attention away from the environment without users noticing. In contrast, *TurnMarker* required more visual searching and effort to interpret, making its impact on SA more noticeable. Users seem to be more aware of distraction when it stems from having to actively search for cues, rather than from cues that passively and continuously guide their attention.

8 Limitations and Future Work

Despite the significant results, several limitations should be acknowledged. First, the study focused exclusively on visual cues, leaving out other techniques such as audio or haptic feedback, which may also influence users SA and performance. Additionally, our manipulation of cue density was limited to spatial frequency; alternative approaches, such as varying transparency, line thickness, or animation, could provide further insights.

The design of anomalies also posed limitations. All anomalies in our study were static and relatively uniform in presentation. Including a wider range of anomaly types, as well as varying their difficulty levels, could have offered a more nuanced understanding of the influence of navigation cues on anomaly detection. In our current worked we analyzed eye tracking data, and although it led to interesting findings we suggest a more detailed and thorough analysis of this data to gain more information.

Our study examined effects of navigation cue in a large-scale, reality-inspired VR environment. While our research questions are relevant to AR contexts, results are not directly transferable and further investigation due to fundamental differences between VR and real world: (i) spatial knowledge acquired in VR may not be transferable to the real world. Indeed, virtual reality (VR), a systematic underestimation of distances, so called compression of virtual space , can significantly impair the transfer of spatial knowledge from virtual to real environments [48, 17]. Although naturalistic real-world stimuli significantly mitigate or fully overcome distance compression [49]. Lack of self-motion also causes a proprioceptive-vestibular mismatch [11, 51] while interfaces allowing to physically walk, such as omnidirectional treadmills (ODT) abide a more congruent sensorimotor feedback [67]. ODTs have drawbacks such as altered gait dynamics and lack of terrain textures [40]. Yet, studies with ODTs are scarce and often with different platforms. In our study, the ODT is a common locomotion device for all participants and trials. Further studies are required to investigate the RQs while walking normally in the real-world. Our research addresses attentional aspects derived from interference arising from cue visual density. Studying such in AR requires careful display considerations. Optical-see-thru AR displays suffer color blending problem [58] while Video-see-thru have to deal with camera-display settings. Hence, an AR study with similar hypothesis to ours should consider display issues. Our study did not consider technical constraints of AR headsets like a limited field of view, registration errors or occlusion handling. These factors may also influence user behavior in AR contexts.

Further research could also study effects of cue density on other cognitive or perceptual processes, like spatial memory.

In future work, it would be valuable to further investigate how user knowledge and experience might influence the effectiveness of different cue designs. Our current results may change depending on factors such as user expertise. Novices may require more frequent or prominent cues, while expert users might prefer subtler, less intrusive guidance. Another direction for future research could be the development of adaptive navigation systems that can dynamically adjust the density and type of cues based on the user's context and needs. Such a system could alter cue density based on environmental factors (e.g., presence of hazards or task complexity) or user-specific factors (e.g., cognitive load, expertise level, or personal preferences). This adaptive approach could help optimize the user experience and performance across different user groups and contexts.

9 Conclusion

Our study demonstrates that even subtle variations in navigation cue design, in our case cue density, can meaningfully influence user awareness and their subjective experience, without compromising task performance.

ArrowTrail, our medium-density cue, outperformed the others in anomaly detection speed and subtle anomaly recognition, indicating enhanced SA. It also maintained a favorable balance between perceived navigational support and unobtrusiveness, which was reflected in both user preferences and lower perceived workload.

While the results are clear within our context, we do not claim that there is a universally optimal cue density. The observed effects are specific to our user group, environment, and task. Outcomes may differ under different conditions. However, our work highlights that even small visual design decisions, such as how densely cues are presented, can have a notable impact on user experience and SA and should therefore be considered a design factor in the development of navigation systems.

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