Emergency Escape – Navigation Using Multimodal Sensory Feedback

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Abstract

Effective evacuation guidance is essential in emergency situations where individuals must rapidly process navigation cues and make timely decisions. While previous research has explored the effectiveness of individual sensory modalities such as visual, auditory, and haptic feedback, limited attention has been given to their combined effects. This study investigated how combinations of auditory, haptic, and visual feedback influence navigation time, confidence in the navigation system, and perceived level difficulty in a virtual reality (VR) navigation scenario. 18 participants completed navigation tasks in a VR simulation of a building, experiencing three different feedback conditions: auditory & haptic, visual & haptic, and visual & auditory. The results showed significant differences in confidence ratings across conditions, with participants reporting the highest confidence in the auditory and haptic condition. However, no significant differences were found in navigation times or perceived level difficulty between conditions. Qualitative feedback further revealed that participants preferred the auditory-haptic combination for its intuitiveness and ease of use. These findings align with theories of human perception and decision making, suggesting that multimodal feedback enhances both cognitive processing and perceived control, ultimately improving user experience during evacuation. The results emphasize the importance of designing evacuation systems that integrate intuitive and redundant multimodal cues to support effective navigation.

Emergency Escape – Navigation Using Multimodal Sensory Feedback

Fast and efficient evacuation is essential in indoor emergencies like extreme weather conditions or fire. Buildings are typically equipped with standard evacuation measures, such as exit signs or drills. However, there are numerous real-life examples of the potential failures of such systems, leading to severe injuries or mortalities (Chen et al., 2021). For example, during a large restaurant fire in Taiwan which affected over 100 guests and staff, people died due to inadequate and obscured evacuation routes during the emergency (Lin & Wu, 2018). Research indicates that only 6–8% of people in real fires even notice static exit signs (Kinkel et al., 2024) and visibility drops drastically as smoke density increases, even for illuminated signs, meaning they are only effective in light smoke conditions (Yamada et al., 2004).

Evacuation becomes even more challenging in modern buildings, as complex interior layouts and large crowds introduce new factors that must be considered in evacuation planning (Abdul Halim et al., 2022). For example, Wang et al. (2017) found that at least 46% of individuals affected by high-rise apartment fires die near the exit due to overcrowding. This occurred because current evacuation systems typically direct individuals to the nearest exit which may not be the safest or most efficient route, especially if it leads to crowding and blocked paths. Together, these limitations (low visibility, low detection rates, and fixed routing) demonstrate that standard evacuation systems fail to meet the demands of real-world emergencies. Therefore, evacuation strategies should move beyond static, pre-designed plans and instead account for dynamic factors such as crowd movement, architectural complexity and individual differences among evacuees (Abdul Halim et al., 2022).

Situation-Aware Systems

To address the shortcomings of standard evacuation signs, researchers have developed situation-aware navigation systems that adapt evacuation routes in real-time to changing environmental conditions. Inoue et al. (2008) noted that GPS is too imprecise for indoor use. Therefore, most situation-aware systems rely on pre-installed radio beacon devices. These systems locate and direct individuals to the best exit using mobile phones or other electronic devices. The environment is continuously monitored via sensors, such as temperature detectors, smoke detectors, cameras, and radars for blocked exits, providing a comprehensive overview of path conditions. When an evacuation path is blocked (e.g., by fire), dynamic route algorithms automatically adjust to redirect evacuees away from danger (Aedo et al., 2016; Inoue et al., 2008; Morales et al., 2014).

These systems have proven to be more effective than static signage, especially when threats obstruct traditional routes. Furthermore, user satisfaction assessments show that situation-aware systems are perceived as more satisfactory, relevant, and less frustrating (Aedo et al., 2016; Morales et al., 2014). Zhang et al. (2020) showed that adapting evacuation routes to real-time congestion further improves evacuation efficiency. Lastly, faster and safer evacuations were observed, which are the primary goals in emergency situations (Lopez-Carmona & Paricio Garcia, 2021).

Despite their advantages, such systems still face limitations. They rely on pre-installed beacons, which may not be available or functional in all buildings (Inoue et al., 2008). Aedo et al. (2016) pointed out that route planning is still based on predicted paths and does not always account for dynamic changes during the evacuation itself. As a result, personalized alerts may become outdated or unclear under evolving conditions. Additionally, users sometimes struggle with dynamic instructions presented alongside traditional signage, causing confusion and cognitive overload (Morales et al., 2014). This highlights the importance of not only adapting routes but also ensuring that instructions are clear, intuitive, and perceptually accessible to ensure the system's overall effectiveness.

Sensory Input

Theories of direct perception propose that certain sensory inputs can be directly picked up from the environment with minimal cognitive processing, allowing for fast and intuitive recognition (Gibson, 1969). In line with this, Spence and Ho (2008) emphasize that well-designed sensory warning signals may be processed rapidly and automatically, enhancing reaction times even under time pressure. Extensive research has applied these insights to the development of sensory-based evacuation systems, demonstrating how well-designed sensory cues can enhance navigation performance.

For example, auditory signals have shown promise in guiding individuals during emergencies. Tronstad et al. (2021) demonstrated that both clicking and tone-based sounds significantly improved participants' ability to navigate evacuation routes in smoke-filled tunnels, with prior instructions further enhancing performance. Similarly, Van Wijngaarden et al. (2005) found that providing prior instructions to follow auditory cues improved participants' evacuation performance significantly. Subjective feedback highlighted the effectiveness, as participants rated tone-based signals as clear, comfortable, and easy to interpret. Furthermore, Aoki et al. (2020) successfully employed the precedence effect, a psychological phenomenon where the first sound heard in an environment influences direction-finding, to guide individuals to the nearest emergency exit. This effect can be crucial in ensuring evacuees follow auditory cues to the best exit. Overall, these findings demonstrate that auditory cues can be effective evacuation tools, especially in visually obstructed environments.

In addition to auditory feedback, research has also highlighted the value of haptic feedback in evacuation contexts. Pielot et al. (2009) examined how tactile directional cues provided through a wearable belt could support navigation. Participants using the tactile belt reached destinations more efficiently, consulted maps less frequently and experienced fewer moments of disorientation. The haptic feedback allowed users to remain oriented without relying on visual or auditory input, making it particularly useful in chaotic, noisy, or visually obstructed situations which are typical emergency evacuations. Extending these findings, Khaliq et al. (2021) showed that vibrotactile guidance significantly improved participants' ability to orient themselves and respond effectively to spatial changes, even when vision and hearing were compromised. Together, these studies underscore the critical role of haptic feedback in improving evacuee navigation, especially when other sensory modalities are impaired.

Finally, Busche (2025) compared haptic, auditory, and visual navigation feedback in a virtual reality (VR) evacuation task. His findings indicated that escape times were consistent across all three conditions, suggesting that haptic and auditory feedback were as effective as visual feedback in supporting evacuation performance. Notably, participants reported significantly higher confidence when following haptic and auditory feedback compared to visual cues. According to Pekrun (2006), confidence arises when individuals feel in control, which reduces anxiety and enhances decision-making (Lee & Hare, 2023), whereas low confidence slows down responses (Siligato et al., 2024). Therefore, facilitating high confidence through appropriate sensory feedback is essential for supporting fast evacuation behaviour.

Multimodal Feedback

In dynamic and high-stakes environments such as emergency evacuations, the ability to perceive and respond to guidance signals is often compromised by environmental factors, cognitive load and stress. Evacuees must detect evacuation signals (e.g., sounds, signs, or vibrations), understand their meaning, and anticipate the consequences of following them. Without this awareness, evacuation systems will fail to guide individuals to safety (Endsley, 1995). For example, when evacuation signals are unclear or perceived as irrelevant due to environmental distractions, such as noise or smoke, individuals may fail to distinguish these signals from background noise. In such cases, signals like lights, sounds, or vibrations need to be strong, clear and redundant to ensure they stand out against distractions like crowd noise or alarms (Green & Swets, 1966). Multimodal feedback systems, which combine auditory, haptic, and visual cues, address these challenges.

One of the key advantages of multimodal systems lies in redundancy gain, meaning that presenting the same evacuation information through multiple sensory channels decreases response latency, reduces error rate as well as strengthens responses (Shepherdson & Miller, 2014). Furthermore, multimodal feedback reduces cognitive load by simplifying the interpretation of evacuation cues. Therefore, individuals can respond more quickly, while also being able to allocate mental resources to other important tasks, such as staying aware of their surroundings or making strategic decisions (Sweller, 1988). In evacuation contexts the environment may unpredictably impair one or more sensory modalities. Dense smoke can limit visual perception, people screaming can mask auditory cues and physical barriers may interfere with haptic feedback. By distributing critical information across multiple sensory pathways, redundancy gain and reduced cognitive load ensure that individuals are still able to receive and act efficiently on evacuation instructions even when certain modalities are occupied.

Beyond this, multimodal feedback also contributes to attentional salience by increasing the overall perceptual prominence of evacuation cues. Multisensory integration allows the brain to combine sub-threshold signals across sensory channels into a unified, more salient cue (Laboratoire des Systèmes Perceptifs, 2018; Wickens, 2008). This is especially relevant in emergency situations, where individuals may experience divided attention, confusion, and stress-related impairments in processing efficiency. Empirical evidence supports this notion: Baldwin et al. (2012) demonstrated that combining auditory and haptic alerts increased perceived urgency and improved response speed compared to unimodal alerts. Their findings suggest that multimodal systems not only compensate for degraded sensory conditions but actively enhance the immediacy and clarity of evacuation signals.

Lylykangas et al. (2016) provide additional support for the robustness of multimodal feedback. Their study, which examined reaction times to visual, tactile, and combined visual-tactile alerts, found that participants responded significantly faster to combined signals, particularly when their visual attention was occupied elsewhere. Moreover, multimodal signals can compensate for age-related reaction time delays observed with unimodal signals, allowing older participants to respond as quickly as younger individuals (Laurienti et al., 2006). These findings underscore the advantage of multimodal feedback in reaction times which is especially important during emergency evacuations.

Taken together, these discoveries illustrate that multimodal feedback not only enhances the detectability of evacuation cues but also supports faster and more reliable decision-making by increasing attentional salience. As such, the integration of multimodal cues promises a highly effective strategy for improving evacuations, particularly in complex and unpredictable emergency scenarios.

Research Gap and Current Study

While various situation-aware systems have been developed to improve navigation, most focus on individual sensory feedback modalities (Tronstad et al., 2021, Pielot et al., 2009, Busche, 2025). Although these systems show promise, their combined effect remains largely unexplored even though research showed that multimodal systems seem promising as they are more situation resilient and prompt faster responses (Baldwin et al., 2012, Lylykangas et al., 2016). Therefore, it remains necessary to examine whether combining sensory cues can further enhance evacuation performance.

This study seeks to address this gap by following the advice of Busche (2025) and expanding his research on individual feedback modalities by investigating how combinations of auditory, haptic, and visual feedback affect navigation performance. Following, this study aims to investigate: *How do different combinations of auditory, haptic, and visual feedback impact participants' confidence in the navigation system, perceived level difficult, and navigation time in a simulated navigation task?*

As Busche´s (2025) results show that haptic and auditive feedback significantly improved confidence in the navigation system, the combination of haptic and auditive feedback should reveal significantly higher confidence in the navigation system compared to multimodal navigation using visual feedback. Furthermore, participants should rate the levels in the auditory and haptic condition as least difficult as confidence increases when people feel most capable of escaping (Pekrun, 2006). Therefore, it is hypothesised that the combination of auditive and haptic feedback will lead to significantly higher confidence in the navigation system and lower-level difficulty ratings than combinations of visual and haptic and visual and auditive feedback.

H1: Participants will have higher confidence in the navigation system and experience the levels as less difficult in the haptic and auditive condition compared to the auditory and visual condition and the haptic and visual condition.

Secondly, in accordance with Busche's (2025) results it is hypothesised that navigation time will not significantly vary across the three conditions auditive and haptic, auditive and visual and haptic and visual feedback.

H2: Navigation time will not significantly differ across the three conditions.

Methods

Design

This study aimed to examine whether a navigation system using multimodal sensory cues functions effectively, and whether certain cue combinations outperform others. A within-subjects experimental design with a repeated measures structure was employed. The study employed a one-factor design with three levels of sensory input (auditory & haptic, visual & auditory, visual & haptic). Task difficulty varied across trials but was not included as a factor in the main hypothesis testing.

Therefore, each participant took part in three sessions, experiencing one of the three navigational cues in each, so they encountered all three sensory inputs by the end of the experiment. Within each session, participants experienced the three difficulty levels. The order in which the participants experienced the different combinations of sensory input was randomized to combat learning effects. The dependent variables included perceived difficulty of each level, confidence in following the signals and navigation time.

Participants

This study included students from the University of Twente, the Netherlands, and additional volunteers recruited through personal contacts. Eligible participants had to be at least 18 years old, possess normal or corrected-to-normal vision and hearing, have no history of epilepsy or severe motion sickness and be capable of participating in all three study phases. Additionally, participation required having a sufficient proficiency in English to accurately engage in the study activities.

A total of 25 participants were recruited. 7 participants did not complete all three sessions and were therefore excluded. This left a final sample of 18 participants, consisting of 10 females and 8 males. Participants' ages ranged from 22 to 57, with a mean age of 32.5 (SD = 13.95). Of the participants, 17 were German and 1 was Dutch.

Ethical approval was obtained from the Ethics Committee of the Faculty of Behavioural, Management and Social Sciences at the University of Twente (Approval Number 250233). Informed consent was obtained from all participants prior to their involvement in the study.

Materials

Virtual Environment

The study featured a VR replication of the Cubicus building, located on the University of Twente campus (Enschede, the Netherlands), which was displayed to the participants using the Meta Quest 2 VR-headset and its motion controllers. The Cubicus building is known for its complex and contorted architecture which makes navigation difficult. For example, Figure 1 consists of actual pictures of the Cubicus building showing signs pointing to the stairs closest to the entrance, visualizing its unclear design.

Figure 1

Pictures of Signs Pointing to the Nearest Exit in the Cubicus Building.

The VR environment was designed to closely match the building's overall architecture, though only minimal furniture and colour matching were included to avoid that participants use such cues as orientation points. The VR replication consisted of the three levels of the original building and its six stairs. Elevators were not included in the VR environment and most doors to offices were closed and could not be opened. However, a few doors were open to simulate dead ends. The VR environment did not simulate any catastrophes, such as fires. Refer to Figures 2a to 2d for pictures of the VR environment.

Figure 2a

Layout of the 3rd Floor.

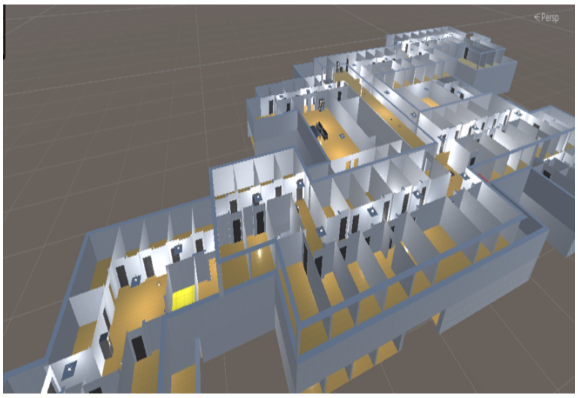


Figure 2b

Staircase 2nd Floor.

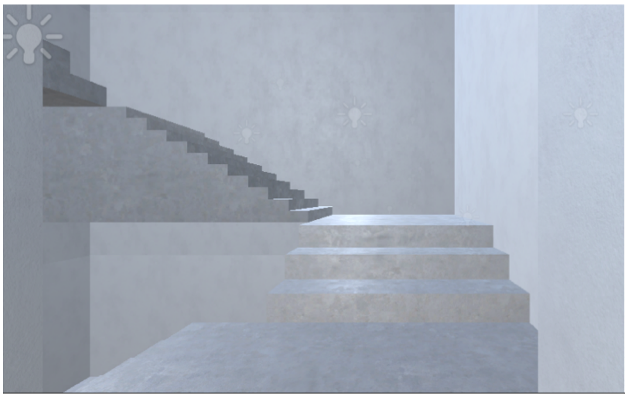


Figure 2c

Exit of the Building on 1st Floor.

Figure 2d

Top View of the Building.

Paths

During each session, participants were required to complete 15 levels. These levels were randomly selected from a pool of 63 pre-designed routes. Each level consisted of a unique path leading to the exit. The 63 available paths were evenly categorized into three levels of difficulty: easy (21), medium (21), and hard (21). Difficulty was determined based on features such as the number of staircases, the use of less intuitive routes, and the presence of turns around corners.

To guide the participants along these paths, invisible checkpoints were placed every five meters. Although participants could not see them, reaching a checkpoint led to an auditory signal, a vibration through the controller and the screen of the mobile phone in the virtual hand flashing green once (see Figure 3). This provided participants with feedback on their progress.

Figure 3

The displayed mobile phone in the participants right hand in the VR environment.

Navigation

Participants were guided through the building using different forms of sensory input. The path they were required to follow was marked by several checkpoints, with sensory input directing them toward each checkpoint. The intensity of the sensory input increased as participants approached a checkpoint and decreased as they moved further away. Upon reaching a checkpoint the sensory input restarted at a lower level. Each checkpoint could only be used once before becoming inactive. In addition, a locomotion system was integrated to allow participants to navigate the building with a walking motion that mimics natural movement. The movement speed was set to two units per second, roughly equivalent to 7.2 km/h. Running was disabled to ensure that navigation times were solely influenced by navigation skills, making the navigation times more comparable.

During the VR trials, participants saw a phone displayed in their right hand, which served as the visual input. The phone's light would illuminate at regular intervals, with the lighting speed increasing as participants came closer to a checkpoint. The haptic feedback was delivered through vibrations in the right-hand controller, simulating the phone vibrating. The intervals between the vibrations decreased as participants approached a checkpoint. The auditory feedback came from the VR headset, producing a small beeping sound. The number of beeps increased and got louder as participants got closer to a checkpoint.

The participants had no control over the sensory input as they were purely passive in response to the movements of the participants in the VR environment. The sensory input could also not be adjusted and therefore were the same for every participant.

Set Up

There were no specific requirements for the layout or equipment of the room where the experiment was conducted, as all necessary equipment was provided by the researcher. The room needed to be large enough for the participants to sit and move freely while using the VR headset. It should also be quiet to prevent distractions or confounding noises.

The virtual environment was experienced using the Meta Quest 2 headset and its accompanying controllers. This device was chosen for its user-friendly design, making it suitable for experimental use with minimal time required for setting up the experiment.

Several programs were employed to develop and operate the VR environment, Unity was used as the development platform, allowing the creation of the virtual environment, the integration of the sensory feedback and the programming of checkpoints and navigation paths. Steam and SteamVR were used to establish a stable connection between the Meta Quest 2 headset and the computer running the virtual environment. Finally, GitHub was used to save different versions of the project, so changes could be tracked and reversed if needed.

Questionnaires

Before the start of the study, participants completed two questionnaires which investigated the participants navigation skills.

Santa Barbara Sense of Direction Scale. The first questionnaire is the Santa Barbara Sense of Direction Scale (SBSOD) which was developed to reflect individuals' capacity to navigate spatial environments (Hegarty Spatial Thinking Lab, n.d.). The scale consists of 15 items which the participant must answer using a 7-point Likert scale, with 1 indicating a strong agreement with the statement and 7 indicating a strong disagreement. The questionnaire used statements like "I am very good at judging distances" or "I have trouble understanding directions" (Hegarty et al., 2002). The SBSOD was chosen as a reliable measure as it has high internal consistency and internal reliability (Cronbach's $\alpha = .88$) as well as a test-retest reliability of .91. Refer to Appendix A for the complete scale.

Wayfinding Questionnaire. The second questionnaire is the Wayfinding Questionnaire (WQ) which assess individual differences in wayfinding ability (Rooji et al., 2017). The scale consists of 22 items, which the participant must answer using a 7-point Likert scale, with 1 indicating that the item is not at all applicable to the individual and 7 indicating that the item is fully applicable to the individual.

The questionnaire consists of three subscale, the first one being “navigation and orientation” using 11 items like “When I am in a building for the first time, I can easily point to the main entrance of this building.” and “I can always orient myself quickly and correctly when I am in an unknown environment.” to investigate how individuals typically find their way/ which strategies they use to orient themselves.

The second subscale, called “Distant estimation”, consists of three items capturing how accurately individuals believe they can judge distances between locations in an environment. Two examples are “Without a map, I can estimate the distance of a route I have walked well, when I walk it for the first time.” and “I can estimate well how long it will take me to walk a route in an unknown city when I see the route on a map (with a legend and scale).”.

The last subscale is called “Spatial anxiety” and uses 8 items like “I am afraid of losing my way somewhere.” or “I am afraid of getting lost in an unknown city.” to measure the degree of anxiety or stress individuals experience when navigating, especially in unfamiliar places.

The reliability of the three subscales has been rated as “very good” and the scale shows acceptable internal consistency. It is suitable for identifying navigation complaints in healthy individuals and stroke patients (Claessen et al., 2016). Refer to Appendix B for the complete Questionnaire.

Prior Cubicus Knowledge. In addition to the two questionnaires, the participants were asked whether they are or where students or staff member of the University of Twente. If they answered with yes, the participant had to fill out a few questions like “On average, how often did you visit the Cubicus building during a semester before the renovation?” or “How confident are you to find a random room in the Cubicus?” to assess prior knowledge about the building’s architecture (refer to Appendix D for the complete questionnaire).

Confidence & Difficulty Ratings. After all questionnaires have been answered, the experiment started. During each of the three trials, participants completed 15 levels. After each level, the researcher asked participants two questions to avoid the need for them to remove the VR headset, making the process more efficient.

Participants were first asked: *"Please indicate how difficult you found the level you just played,"* and were instructed to provide a number between 1 and 100, where 1 represented "very easy" and 100 represented "very difficult." Next, they were asked: *"Please indicate how confident you were in following the signals of the device,"* again responding with a number between 1 and 100, where 1 indicated "not confident" and 100 indicated "very confident."

At the end of each of the three sessions, participants were asked to fill out two open-ended questions: *"Do you think that the device helped you to navigate the building and find your way out? Why or why not?"* and *"What would you improve to make the device more helpful?"*

In the final third session, participants were also asked an additional question: *"Think about the three sessions you have completed, especially the three different combinations of sensory input. Please compare them and describe how they differed in the way they helped you to navigate."*

Procedure

Participants from the University of Twente were recruited through an internal online platform. Upon completing the study, this platform awards participants with credits necessary to fulfil the participants' study requirements.

The participants could choose a time slot for each session. Furthermore, depending on the participant, the sessions were held in the University of Twente or in rooms outside the University setting that fitted the requirements.

The researcher welcomed the participant and reminded them of the study's aim, voluntary participation, the ability to withdraw from the study at any point without any consequences except the loss of credits, and the risk of motion sickness. Furthermore, the researcher explained the procedure to the participant and instructed them to tell the researcher immediately if any questions should arise during the experiment or if any discomfort is experienced.

Following, the participant filled out a questionnaire which included informed consent as well as some demographic questions like gender, age, nationality and education (refer to Appendix C for the consent form). Next, participants who are students or employees of the University of Twente filled out a questionnaire regarding their knowledge of the Cubicus building. Lastly, all participants filled out the SBSOD as well as the WQ scale. All of this was only done once during the first session.

After this, the participant received instructions on how to navigate in the VR Environment and the researcher placed the VR headset as well as the controllers on the participant. The participants then played a tutorial level to get used to the VR environment, its workings as well as the sensory feedback. Once the participants felt comfortable using the device, the experimenter started the first level of the experiment. After the participant finished the first level, the experimenter asked the first questions *"Please indicate how difficult you found the level you just played,"* to which the participant had to verbally answer a number raging from 0 to 100. Following, the researcher asked the second question *"Please indicate* *how confident you were in following the signals of the device."* to which the participant again verbally answered with a number between 0 to 100. Following, the researcher asked if the participant was ready for the next level or needed a break. This procedure was repeated 15 times. Figure 4a depicts the study setup, figure 4b shows the researcher asking the participant the two questions regarding the perceived difficulty and confidence.

Figure 4a

Exemplary Experiment Set-Up.

Figure 4b

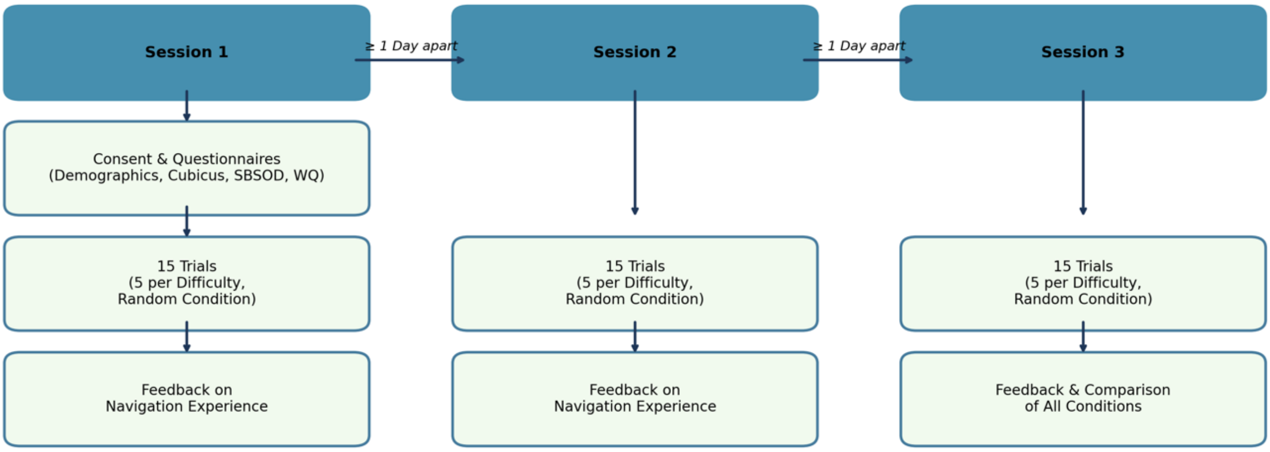
Exemplary Difficulty and Confidence Rating.

After 15 levels were played, the participant was instructed to take off the headset and answer the two open questions on the laptop "*Do you think that the device helped you to navigate the building and find your way out? Why or why not?*" and "*What would you improve in order to make the device more helpful?*". During the third session, there was one more question following the two, namely *"Think about the three sessions you have completed, especially the three different combinations of sensory input. Please compare them and describe how they differed in the way they helped you to navigate."*.

After completing the final level, the researcher scheduled the next session with the participant and the participant could leave the experiment. Figure 5 illustrates the whole process.

Figure 5

Procedure of the Experiment.



Data Analysis

This study collected quantitative and qualitative data to investigate how different multimodal sensory conditions affect participants' navigation performance and experience. Quantitative data included navigation time (how long participants took to complete each path), self-reported difficulty rating of the level and self-reported confidence ratings after each level. These variables were measured across three sensory conditions in three sessions. Demographic characteristics and participants' familiarity with the Cubicus building were also recorded to explore their potential influence on performance and ratings.

To analyse the differences in performance across the conditions, a series of repeated measures ANOVAs (Analysis of Variance) were conducted. This statistical method is suitable when the same participants are measured under multiple conditions, which are in this case, the three sensory modalities (visual, auditory, haptic). Specifically, the ANOVAs tested whether the mean navigation times, confidence ratings and perceived difficulty significantly differed depending on the sensory input. If the ANOVA results indicated statistically significant effects, post-hoc tests were performed to determine which specific condition differed from the others. This was used to identify whether participants performed significantly faster or felt more confident under one sensory condition compared to another. In addition, correlational analyses were used to examine whether demographic variables (such as age or gender), prior knowledge of the Cubicus device, or self-reported wayfinding tendencies (using the results of the SBSOD and WQ) were related to escape performance. Lastly, qualitative data from participants' open-ended feedback was analysed to identify recurring themes and suggestions that could help to improve the device.

Results

Descriptive Statistics

The sample included participants with varying educational backgrounds: 7 reported completing high school, 7 finished vocational training, and 4 held a bachelor's degree. Half of the participants (N = 9) identified as current or former students or staff at the University of Twente, while the other half (N = 9) indicated they were not affiliated with the university. Among the affiliated participants, 7 reported having been at the university for 2–3 years, and 2 for more than 3 years.

Regarding familiarity with the Cubicus building, 10 participants had previously been inside, while 8 had not. When asked how often they visited the building before renovation, 4 participants reported visiting once a week, 2 multiple times a week, and 4 almost never. Participants were also asked to rate their confidence in finding a random room in the Cubicus on a scale from 0 to 100. Responses varied widely, ranging from 15 to 85. Additionally, 10 participants reported having gotten lost in the Cubicus before, with 7 indicating this occurred "often" and 3 selecting "sometimes."

The mean score on the SBSOD scale was M = 3.60 (SD = 0.86), indicating that participants, on average, reported a moderate sense of direction, neither particularly strong nor weak. The mean score of the subscale Navigation and Orientation on the WQ was M = 17.45 (SD = 25.05) which indicates a non-impaired score. The mean score of the Spatial Anxiety subscale was M = 12.59 (SD = 18.25) which again demonstrates a non-impaired score. On the last subscale Distance Estimation, the mean score was M = 3.83 (SD = 5.74) which is a non-impaired score. These results suggest that participants, on average, exhibit typical levels of navigation ability, spatial anxiety and distance estimation, with no significant difficulties or impairments.

Hypothesis One

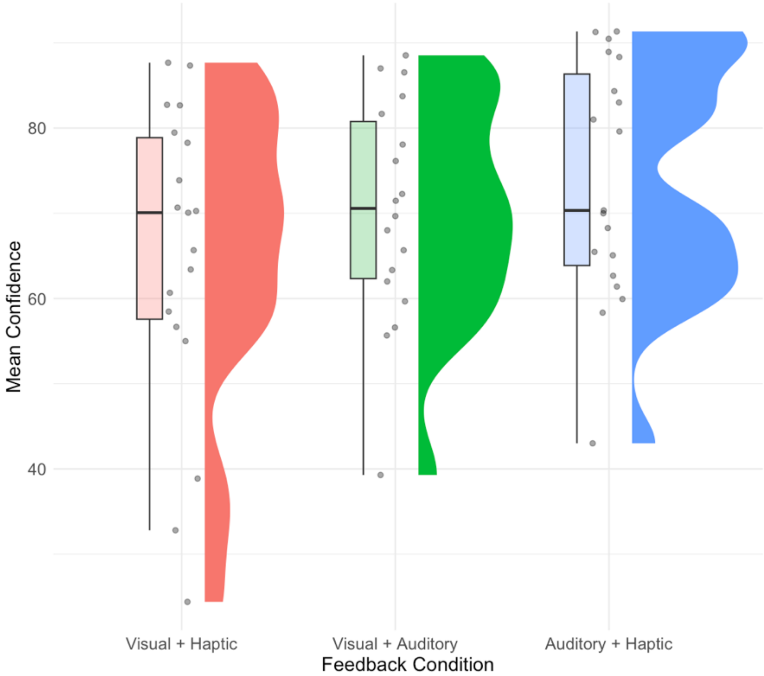
Confidence Ratings Across Conditions

On average, participants reported a mean confidence rating of M = 69.19 (SD = 15.28) across all conditions. Confidence was measured on a scale from 0 (not confident at all) to 100 (extremely confident) indicating that participants felt moderately to highly confident in following the signals.

A factorial repeated-measures ANOVA was conducted to examine differences in mean confidence ratings across the three feedback conditions: visual & haptic, visual & auditory, and auditory & haptic. The main effect of condition was statistically significant, F (2, 34) = 3.39, p = .045, η^2=0.17, visualized in Figure 6.

Figure 6

Confidence Ratings by Feedback Condition.



Note. Raincloud plot depicting mean confidence ratings across the three feedback conditions: visual & haptic, visual & auditory, and auditory & haptic. Each condition includes a boxplot (showing median and interquartile range), individual data points and a half-violin plot representing the distribution of confidence scores. Confidence ratings appear to vary significantly across conditions.

Paired-sample t-tests were applied to compare the conditions. The results of the t-tests are summarised in table one. After Holm correction, confidence was not significantly lower in the visual & haptic condition (M = 63.96, SD = 17.59) compared to the auditory & haptic condition (M = 73.32, SD = 14.11). Similarly, no significant differences were found between the visual & haptic condition (M = 63.96, SD = 17.59) and the visual & auditory condition (M = 70.29, SD = 13.07), or between the visual & auditory condition (M = 70.29, SD = 13.07) and auditory & haptic condition (M = 73.32, SD = 14.11).

Table 1

Pairwise Comparisons of Confidence Ratings Across Feedback Conditions.

	Mean Difference	*t* (17)	*p*	*p* (Holm)	Cohen's *d*	CI
Visual & Haptic vs Auditory & Haptic	–9.36	-2.19	.043	.129	-0.52	-18.38 -0.33
Visual & Haptic vs Visual & Auditory	–6.33	-1.80	.090	.129	-0.42	-13.78 1.11
Visual & Auditory vs Auditory & Haptic	–3.03	-0.98	.343	.343	-0.23	-9.56 3.51

To account for potential effects of repeated testing, a linear mixed model (LMM) was fitted with Condition, Session, and their interaction as fixed effects and participant ID as a random intercept. The model revealed no significant main or interaction effects (all *p*s > .05), indicating that confidence ratings remained stable across sessions regardless of feedback modality.

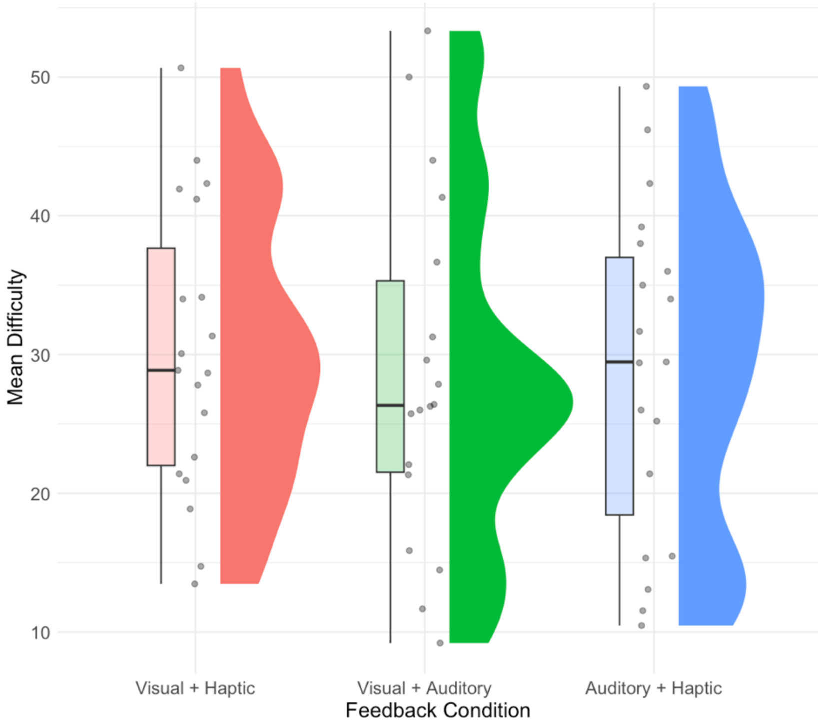
Difficulty Ratings Across Conditions

On average, participants reported a mean difficulty rating of M = 29.53 (SD = 11.47) across all conditions. Difficulty was measured on a scale from 0 (not difficult at all) to 100 (extermely difficult) indicating that participants experienced the levels as low in difficulty.

A repeated-measures ANOVA on perceived difficulty ratings revealed no significant main effect of Condition, (F (2, 34) = 0.55, p = .583, η^2=0.03). This suggests that participants perceived the levels as similar in difficulty regardless of the feedback combination, as visualized in Figure 7.

Figure 7

Difficulty Ratings by Feedback Condition.



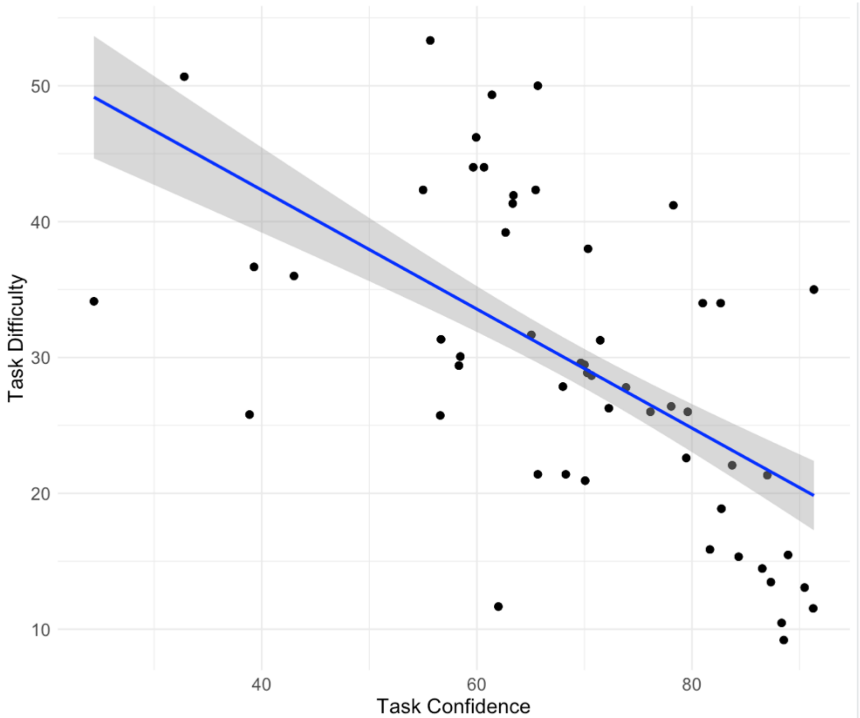
Note. Raincloud plot depicting mean difficulty ratings across the three feedback conditions: visual & haptic, visual & auditory, and auditory & haptic. Each condition includes a boxplot (showing median and interquartile range), individual data points, and a half-violin plot representing the distribution of difficulty scores. Difficulty ratings appear to not vary significantly across conditions.

The LMM analysis likewise showed no significant fixed effects for Condition, Session, or their interaction (all *ps* > .5). Overall, these results indicate that perceived task difficulty was unaffected by the type of sensory feedback or session progression.

However, correlational analysis revealed that confidence in the signals and task difficulty was strongly negatively correlated, r (160) = –.58, $p < .001$, indicating that participants who felt more confident also perceived the task as less difficult, as illustrated in figure eight.

Figure 8

Relationship between Task Confidence Ratings and Task Difficulty Ratings.



Note. Scatterplot depicting the relationship between task confidence ratings and task difficulty ratings. Each point represents an individual observation. A linear regression line with a 95% confidence interval (shaded area) is included. Results indicate a negative relationship. Higher task confidence is associated with lower perceived task difficulty.

Correlation of Demographics and Confidence & Difficulty Ratings

To explore whether participant demographics were associated with task perceptions, Pearson correlations were conducted between age and gender and mean confidence and mean perceived difficulty.

- Age not significantly correlated with mean confidence, $r = .34$, $p = .167$, 95% CI [–.15, .70], and showed no meaningful association with difficulty ratings, $r = .09$, $p = .713$, 95% CI [–.39, .54].
- Gender did not reach statistical significance when correlated with mean confidence, $r = .42$, $p = .083$, 95% CI [–.06, .74]. No significant association was found between gender and perceived difficulty, $r = –.12$, $p = .644$, 95% CI [–.55, .37].

Correlation of Santa Barbara Sense of Direction and Confidence & Difficulty Ratings

To examine whether individual differences in spatial orientation were associated with task-related perceptions, Pearson correlations were computed between participants' SBSOD scores and their mean confidence and mean perceived difficulty ratings during the task.

- The correlation between SBSOD scores and mean confidence was not statistically significant, $r = -.21$, $p = .134$, 95% CI [–.45, .07].
- No significant relationship was found between SBSOD scores and perceived difficulty, $r = .05$, $p = .740$, 95% CI [–.22, .31].

These results suggest that participants' self-reported sense of direction was not reliably associated with how confident or challenged they felt during the task.

Correlation of Wayfinding Questionnaire and Confidence & Difficulty Ratings

To assess whether spatial navigation strategies were associated with participants' perceptions of the task, Pearson correlations were computed between the three subscales of the Wayfinding Questionnaire (WQ) and mean confidence and mean perceived difficulty.

- Navigation-Oriented Strategies (WQ_NO) were not significantly correlated with mean confidence, $r = .03$, $p = .673$, 95% CI [–.12, .19], nor with mean difficulty, $r = -.01$, $p = .867$, 95% CI [–.17, .14].
- Spatial Anxiety (WQ_SA) was also unrelated to mean confidence, $r = .05$, $p = .545$, 95% CI [–.11, .20], and to mean difficulty, $r = -.05$, $p = .534$, 95% CI [–.20, .11].
- Direction Estimation (WQ_DE) showed no significant correlation with either mean confidence, $r = .05$, $p = .549$, 95% CI [–.11, .20], or mean difficulty, $r = .02$, $p = .849$, 95% CI [–.14, .17].

These findings indicate that participants' self-reported navigation tendencies and spatial anxiety were not associated with how confident or challenged they felt during the task.

Correlation of Cubicus Knowledge and Confidence & Difficulty Ratings

There was no significant correlation between Cubicus visit frequency and task confidence, $r(16) = .34$, $p = .065$. All other associations between Cubicus knowledge (confidence and visit frequency) and task outcomes (confidence and difficulty) were non-significant (*r*s between –.20 and .20, all *p*s > .29).

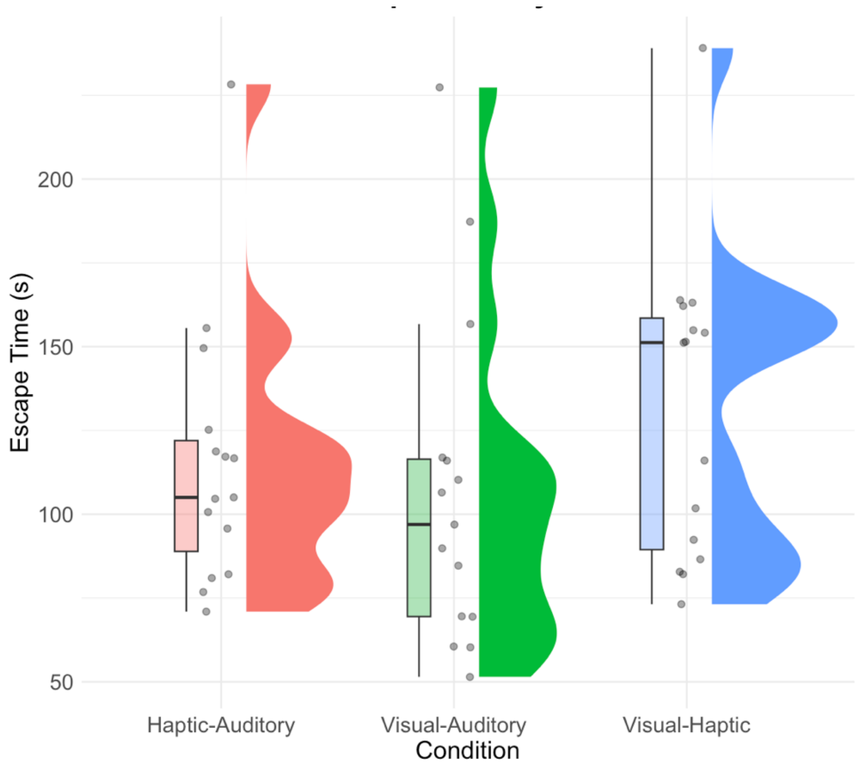
A comparison of the correlation between task confidence and perceived difficulty across participants with high and low Cubicus confidence revealed a larger negative association in the high-confidence group ($r = -.78$) compared to the low-confidence group ($r = -.30$). Fisher's *z*-test for independent correlations indicated that this difference did not reach statistical significance, $z = 1.79$, $p = .074$. Additionally, the 95% confidence interval for the difference between correlations [–0.05, 1.05] included zero, supporting the conclusion that the difference was not statistically significant.

Hypothesis Two: Navigation Times Across Conditions

A repeated-measures ANOVA was conducted to compare navigation times across the three feedback conditions. For this analysis, data from only 15 participants was used due to data loss affecting the remaining cases. The main effect of condition was not statistically significant, F (2, 28) = 2.11, p = .14, η^2 = 0.131 indicating that mean navigation times did not significantly differ across the three conditions (illustrated in Figure 9).

Figure 9

Navigation *Time by Feedback Condition.*



Note. Raincloud plot showing navigation time (in seconds) across the three feedback conditions: haptic & auditory, visual & auditory, and visual & haptic. Each condition includes a half-violin plot (depicting the distribution), a boxplot (showing the median and interquartile range), and the individual data points. While Visual& Haptic shows slightly higher median and variability in navigation times, differences across conditions appear small and were not statistically significant.

Follow-up pairwise comparisons using paired *t*-tests with Holm correction revealed no significant difference between the Visual-Auditory (M = 107, SD = 49.8) and Haptic-Auditory (M = 115, SD = 39.8) conditions, p = .39. Similarly, no significant differences were found between the Visual-Haptic (M = 132, SD = 45.7) and Haptic-Auditory conditions (p = .38), nor between the Visual-Haptic and Visual-Auditory conditions (p = .36).

Qualitative Feedback

Overall, 13 participants (P) indicated that they liked the auditory & haptic condition the most, 1 participant indicated that they preferred the visual & auditory combination, and 1 participant stated that all three conditions were more or less the same. The remaining 3 participants did not indicate a preference for a specific combination.

What participants enjoyed most about the auditory & haptic condition was that “It did not distract” and “only enhanced” the navigation (P4). 7 participants explicitly mentioned that they appreciated that they could still use their visual senses and look around to orient themselves, making navigation and usage “easier and more automatic” (P13). Participant 9 also described it as “very clear and noticeable”.

Many participants highlighted that the haptic feedback was especially helpful for navigation. Phrases like " Especially the haptic signal helped me to quickly get and understand of where to go" (P8) and “(the device) helped, especially the haptic feedback “(P4) suggest it was the most reliable form of guidance. Audio feedback was also frequently mentioned as helpful, particularly the tone increasing in pitch or repetition to indicate correct direction (P13, P 22). However, some participants noted issues with the sound, such as delayed audio or confusing signals (P6, P14). Visual feedback was often considered less helpful or distracting, with comments like “The visual signals were less helpful” (P24), "visual feedback is less helpful than vibration" (P3) and "the blinking phone was not helpful at all." (P19).

Many participants requested more frequent and more divers feedback. For example, the "beeping should be more constant" (P1), “More checkpoints and the signals having more diversity, going from slow to fast" (P4) and "it would help me if the feedback would be more frequent" (P9) as “Sometimes the clues are still a bit unreliable and inconsistent” (P17).

Participants frequently mentioned the need for clear indications when going in the wrong direction, such as "signals when leaving the correct way" (P24), “indicating if a person is on the wrong track” (P13) and "it would be nice to have a signal when you are going in the wrong direction" (P20). Participants further emphasized this by suggesting "you could also use an arrow to give the direction" (P19) and “a visual information on the phone with colours (green for right direction, red for wrong direction)” (P22).

Discussion

This study investigated the effectiveness of multimodal signals in navigating individuals through a VR building. The combinations of auditory & haptic, auditory & visual and haptic & visual signals were compared in regard to navigation time, confidence ratings and difficulty ratings. Through this, this study contributes valuable insights into which multimodal signals work best in navigation and how multimodal navigation might be improved.

Confidence Ratings

It was hypothesised that participants would feel most confident when guided by a combination of haptic and auditory feedback compared to combinations involving visual feedback. Although the statistical analysis only showed partially significant results, the qualitative feedback strongly emphasized a clear preference for the auditory and haptic condition. This is in line with Busche (2025), as their participants had highest confidence in both the auditory and haptic condition compared to the visual condition. Furthermore, these results align with the findings of Khaliq et al. (2021) and Aoki et al. (2020) who demonstrated that auditory and haptic feedback can successfully guide participants to safety, especially when visual cues are compromised.

While the visual sense in this study was not intentionally compromised (e.g., by smoke or poor lighting), several factors may have occupied much of its capacities. The complex architecture of the VR environment and its minimal interior design required participants to actively search for spatial cues, likely demanding a large portion of their visual attention. This is supported by the qualitative feedback as participants expressed a preference for auditory and haptic feedback, noting that it allowed them to continue using their vision to orient themselves and navigate through the virtual building. They appreciated being able to scan their surroundings freely without having to visually focus on the feedback itself (e.g., P4, P13). This is an essential insight as Abdul Halim et al. (2022) already pointed out that complex interior layouts in modern buildings are an important new thing to consider when it comes to evacuation planning.

These findings can further be interpreted through the lens of Signal Detection Theory (Green & Swets, 1966), which suggests that participants may have struggled to detect visual feedback due to the high level of visual noise, e.g. the complex environment and the cognitive effort required for orientation. In contrast, auditory and haptic feedback likely faced less competing sensory input, making them easier to perceive and interpret.

Furthermore, the redundancy gain and multisensory integration of two already clear signals, haptic and auditory, may have enhanced signal clarity even more. In contrast, combinations involving visual feedback may not have benefited from multisensory integration, as participants reported barely noticing or completely overlooking the visual cues (Laboratoire des Systèmes Perceptifs, 2018; Shepherdson & Miller, 2014; P13).

Difficulty Rating

No significant differences were found between the conditions for perceived level difficulty, indicating that participants found the navigation task equally difficult to complete regardless of the multimodal input provided. While this is in line with Busche's (2025) results, it contrasts the control value theory of achievement emotion. As participants felt most comfortable in the auditory and haptic condition, participants should have rated levels there as least difficult. A possible explanation is that participants generally perceived all levels as easy, with an average difficulty rating of 29.53 on a 0-100 scale, indicating that none of the levels presented a substantial challenge. Furthermore, the absence of stressors such as fire or smoke in the VR environment may have reduced the urgency or value of reaching the exit (Pekrun, 2006).

Secondly, the multisensory cues (auditory, haptic and visual) might each have reduced cognitive load, making the task feel more intuitive and straightforward, which could explain why participants rated the difficulty as low throughout. Multimodal signals are often designed to complement each other, thereby simplifying the decision-making process and making tasks easier to follow (Baldwin et al., 2012; Lylykangas et al., 2016). Because these sensory cues were so effective and easy to interpret, participants were able to complete the task with minimal effort, leading to consistently low difficulty ratings, regardless of the feedback combination. This reduction in cognitive load is important since tasks that require less cognitive effort are generally perceived as easier (Sweller, 1988). The ease of interpreting the cues likely outweighed the potential complexity of the levels and environment, meaning that participants didn't experience the task as cognitively demanding. Therefore, although the multisensory combinations increased participants' confidence, they did not affect perceived difficulty, likely because the task was not challenging enough to demand significant cognitive effort.

Correlation Confidence and Difficulty Ratings

The strong negative correlation between confidence and difficulty indicates that as participants' confidence in the task increased, their perception of its difficulty decreased. This relationship suggests that participants who felt more certain about their ability to navigate the task rated it as less challenging, while those who felt less confident perceived the task as more difficult. This finding is consistent with the Control-Value Theory of Achievement Emotion, when individuals believe they can successfully complete a task, they tend to perceive it as less demanding (Pekrun, 2006). This inverse relationship may also reflect how cognitive load is managed: higher confidence could be associated with reduced cognitive strain, making the task feel easier. This finding is significant in evacuation contexts, as confidence has been shown to enhance decision-making, enabling individuals to respond more quickly and with greater certainty which is essential during escape (Lee & Hare, 2023).

Navigation Time

The second hypothesis predicted that navigation times would not significantly differ across the different sensory combinations. The results support this hypothesis, as participants took approximately the same amount of time to navigate the task, regardless of the feedback condition. This finding aligns with the results of Busche (2025), suggesting that alternative feedback modalities (such as haptic and auditory) can provide guidance as effectively as visual cues. However, despite the replication of Busche (2025), which involved the same VR environment and equipment, the use of combined sensory feedback instead of singular feedback implied that participants in this study should have had faster navigation times, as previous research has shown that multimodal signals generally improve performance in navigation tasks (Baldwin et al., 2012; Lylykangas et al., 2016). Interestingly though, a comparison of the mean navigation times between the two studies reveals that Busche (2025) reported significantly faster times, particularly with the visual-haptic combination (132 seconds) compared to the individual visual (81 seconds) and haptic (85 seconds) feedback conditions. One potential explanation for this discrepancy is the age difference between the two samples. Participants in Busche (2025) were significantly younger ($M = 21.38$) compared to those in the current study ($M = 32.5$), which could imply greater familiarity and comfort with using VR headsets in the younger sample (Nicosia et al., 2022). Many participants in this study voiced complaints about handling the VR equipment, further suggesting that a technological familiarity of the younger group in Busche (2025) might have contributed to their faster response times. Interestingly, although participants in the current study had similar results on the Cubicus knowledge questionnaire and SBSOD, their performance on the wayfinding questionnaire was significantly better than that of Busche (2025). This suggests that the difference in navigation times is not due to differences in wayfinding strategies, but rather could be linked to other factors, such as technological comfort or potential VR-related issues.

Another possible explanation is that participants received only a brief introduction to the feedback modalities. Research has shown that providing more detailed instructions can improve the use of sensory inputs for navigation (Tronstad et al., 2021; Van Wijngaarden et al., 2005). As a result, visual feedback may have been more intuitive for participants, as they are more accustomed to using it in daily life (e.g., for navigation). In contrast, the auditory and haptic condition might required a learning curve, which could have balanced out any potential benefits.

Lastly, this study used a set walking speed to ensure more reliable comparisons of navigation times across conditions. However, this prevented participants from increasing their speed when they felt confident in the feedback they were receiving. Consequently, although participants expressed a preference for the auditory and haptic condition, as reflected in the subjective feedback, they might not have been able to adjust their behaviour accordingly in the VR environment.

Limitations

Several limitations should be noted. While the use of a VR environment was intentionally chosen for its cost-effectiveness, experimental control and flexibility, (Chen et al., 2021; Pan & Hamilton, 2018) it also introduced some challenges that may have influenced participants' experiences and performance. Numerous participants reported difficulties navigating within the VR environment. For example, when attempting to turn, many experienced disorientations due to the overly rapid spin of the system, which led to frustration and decreased engagement with the task. This could have contributed to longer navigation times, as some participants unintentionally walked in circles or repeated paths before realizing their mistake which may not happened in a life experiment. Additionally, several participants experienced motion sickness, particularly when using stairs or turning corners. To cope, some closed their eyes or avoided certain movements altogether, likely exacerbating disorientation and delaying task completion. Moreover, because the study deliberately excluded external stressors (e.g., fire, smoke, time pressure) to isolate the effects of navigation alone, some participants approached the task with a more relaxed attitude. A few even stopped to inspect the virtual environment, requiring reminders that they were being timed. These factors suggest that while VR offers a controlled way to simulate evacuation, it may have affected the ecological validity and consistency of the results.

Secondly, although the exclusion of stressors in the VR environment was an intentional design choice to isolate the effect of navigation cues, it made it difficult for participants to understand the necessity of following the guided route. When participants recognized the virtual environment, some chose to follow familiar paths they walked before, especially when the exit was already visible, instead of adhering to the feedback signals. This occurred despite clear instructions to follow only the provided cues. Without realistic obstacles such as fire, smoke or blocked pathways, participants struggled to grasp the relevance of avoiding certain routes, which led to shortcut behaviour that may not be possible in a real-life emergency. Such behaviour may have compromised the validity of the findings, as it does not accurately reflect how individuals might respond under actual emergency conditions.

A third limitation concerns the design of the sensory feedback system itself. Many participants reported that it was difficult to understand and interpret the feedback, especially early in the task. Several participants expressed a preference for more frequent checkpoints, noting that the long walking distances before receiving stronger feedback made it unclear whether they were on the right path. Additionally, participants suggested that the feedback should resume more quickly after each checkpoint and that it should be more sensitive, offering clearer variations to indicate progress. Due to the lack of immediate or noticeable signal changes, some participants who were initially walking in the correct direction turned around prematurely, mistakenly believing they were off course. This likely affected navigation time and may also have influenced confidence in the navigation system and perceived difficulty ratings.

Lastly, although several aspects of the study design were intentionally chosen to ensure standardization and control, such as the use of a VR environment, a fixed walking speed, and simplified instructions for feedback modalities, these elements revealed some unforeseen limitations in practice. The brief instruction period may have hindered participants' ability to fully utilize the haptic and auditory cues, particularly compared to the more intuitive visual feedback. The fixed walking speed, while helpful for comparing navigation times across conditions, limited participants' ability to adjust their behaviour based on their confidence. Additionally, the sample differed from that of Busche (2025) in terms of age and likely VR familiarity, which may have influenced task performance. While these decisions were made for methodological clarity, they also introduced constraints that should be considered when interpreting the results.

Directions for Future Work

As this study has demonstrated the general effectiveness of the proposed multimodal navigation system, future research should investigate whether these findings hold under high-stress conditions that more closely resemble real emergency scenarios. The current study deliberately excluded real-life stressors, such as fire, smoke, crowd dynamics, or time pressure, to test the system's core functionality with minimal confounding variables. However, understanding how users respond to multimodal cues when under acute stress is essential for evaluating the system's real-world applicability. Only then can we assess the system's practical value in real-life evacuations, where confusion, fear, and urgency may impair cognitive processing.

Additionally, future work should explore how the system performs when sensory impairments are present, whether due to environmental conditions (e.g., smoke or darkness), temporary disorientation, or permanent disabilities such as hearing or vision loss. Investigating how individuals with sensory limitations interact with the system is critical to ensuring that evacuation strategies are inclusive and accessible to all populations. Moreover, it would be valuable to explore how the system functions when all three feedback modalities (auditory, haptic, and visual) are provided simultaneously. This could offer insights into whether integrating all channels provides added benefits, or whether certain combinations are already sufficient.

Another open question is why navigation times did not significantly differ between feedback conditions in this study, despite existing research suggesting they should (Wickens, 2008, Baldwin et al., 2012, Lylykangas et al., 2016). This raises the practical concern of whether one multisensory feedback combination truly offers a performance advantage over others, or whether all combinations are equally effective in guiding individuals to safety. Clarifying this could have direct implications for how evacuation systems are designed and how certain combinations may be prioritized in different environments or with different populations.

Finally, this study, along with supporting theoretical frameworks (Pekrun, 2006), emphasizes the role of confidence in evacuation behaviour. In real emergencies, confidence in the guidance system may determine whether individuals follow instructions quickly and accurately. Therefore, future research should explore how to strengthen user confidence under stress, as this could be a decisive factor in saving lives during evacuations.

Practical Implications

Urban planners, safety engineers, and evacuation system designers can use these insights to develop more inclusive and effective evacuation guidance systems. Instead of relying solely on visual signs, which may be inaccessible during emergencies, systems that incorporate redundant multimodal feedback can ensure more individuals are reached (Shepherdson & Miller, 2014). This is particularly relevant in public infrastructure, hospitals, and high-rise buildings, where diverse populations may be present, including elderly individuals or those with sensory disabilities (Lyu & Wang, 2025). Creating systems that support multiple sensory pathways can increase compliance and inclusiveness, reduce panic, and potentially save lives.

Moreover, the study highlights the psychological aspect of user confidence in evacuation contexts. Since participants felt most confident with certain feedback combinations, future safety communication strategies can aim not just to inform but also to reassure and empower evacuees. Confidence is a critical factor in whether individuals follow instructions and make timely decisions during emergencies (Lee & Hare, 2023, Siligato et al., 2024) which may decide over life and death.

Beyond public evacuations, the navigation system explored in this study could also be applied in other contexts where certain senses are compromised. For instance, firefighters navigating in smoke-filled buildings often experience severely reduced visibility, making visual guidance systems practically unusable (Slater et al., 2025). In such scenarios, a multimodal system that combines haptic and auditory cues could support safe and efficient navigation, helping firefighters locate exits or reach missing individuals. This not only highlights the system's flexibility but also its potential to enhance operational safety in high-risk, real-world environments.

In sum, this study provides valuable evidence for the design of inclusive, accessible, and psychologically supportive evacuation systems, offering divers practical applications in public safety. By prioritizing sensory diversity and user experience, such systems can lead to safer environments and more effective evacuations, potentially saving lives.

Conclusion

This study contributes to the growing body of research on evacuation guidance systems by demonstrating that multisensory feedback combinations can effectively support individuals during evacuation scenarios in a virtual reality environment. Unlike previous studies, such as Busche (2025), which focused on singular sensory feedback, this study was the first to systematically compare different combinations of sensory modalities (auditory & haptic, visual & haptic, visual & auditory) to assess their effects on confidence, perceived difficulty and navigation time. The findings show that participants had a strong preference for multimodal feedback using auditory and haptic cues, suggesting that these modalities are highly effective in navigation tasks, especially when visual attention is occupied.

By isolating the effects of sensory feedback without introducing real-world stressors, this study lays the groundwork for future research to explore how multimodal systems can be used and function under realistic emergency conditions. Furthermore, it opens new directions for developing inclusive evacuation strategies, particularly for individuals with sensory limitations or in environments where one or more senses may be impaired.

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Appendix A
Santa Barbara Sense of Direction Scale

The following statements ask you about your spatial and navigational abilities, preferences, and experiences. Please read each statement carefully and indicate how much you agree with that statement on a scale from "1 - Strongly disagree" to "7 - Strongly agree".

1. I am very good at giving directions.
2. I have a poor memory for where I left things
3. I am very good at judging distances.
4. My "Sense of direction" is very good.
5. I tend to think of my environment in terms of cardinal directions (N, S, E, W).
6. I very easily get lost in a new city.
7. I enjoy reading maps.
8. I have trouble understanding directions.
9. I am very good at reading maps.
10. I don´t remember routes very well while riding as a passenger in a car.
11. I don´t enjoy giving directions.
12. It´s not important to me to know where I am.
13. I usually let someone else do the navigational planning for long trips.
14. I can usually remember a new route after I have traveled it only once.
15. I don´t have a very good "mental map" of my environment.

Appendix B
Wayfinding Questionnaire

The next 22 questions will be about navigation. You answer the questions by marking the numbers most suitable to you.

1. When I am in a building for the first time, I can easily point to the main entrance of this building.
2. If I see a landmark (building, monument, intersection) multiple times, I know exactly from which side I have seen that landmark before.
3. In an unknown city I can easily see where I need to go when I read a map on an information board.
4. Without a map, I can estimate the distance of a route I have walked well, when I walk it for the first time.
5. I can estimate well how long it will take me to walk a route in an unknown city when I see the route on a map (with a legend and scale).
6. I can always orient myself quickly and correctly when I am in an unknown environment.
7. I always want to know exactly where I am (meaning, I am always trying to orient myself in an unknown environment).
8. I am afraid of losing my way somewhere.
9. I am afraid of getting lost in an unknown city.
10. In an unknown city, I prefer to walk in a group rather than by myself.
11. When I get lost, I get nervous.
12. I find it frightening to go to a destination I have not been before.
13. I can usually recall a new route after I have walked it once.
14. I am good at estimating distances (e.g., from myself to a building I can see).
15. I am good at understanding and following route descriptions.
16. I am good at giving route descriptions (meaning, explaining a known route to someone).
17. When I exit a store, I do not need to orient myself again to determine where I have to go.
18. I enjoy taking new routes (e.g., shortcuts) to known destinations.
19. I can easily find the shortest route to a known destination.

How uncomfortable are you in the following situations?

20. Deciding where to go when you are just exiting a train, bus, or subway station.
21. Finding your way in an unknown building (e.g., a hospital).
22. Finding your way to a meeting in an unknown city or part of a city.

Appendix C
Informed Consent

Informed Consent Emergency Escape – Navigation with a Fake Phone

During building fires, evacuation gets more difficult as dense smoke can severely impair vision. A tactile, hands-free guidance system, placed in a pocket, could provide crucial assistance in such scenarios, particularly for those guiding others to safety. This study explores such an evacuation approach by using a fake smartphone to deliver directional cues through tactile signals, removing the need for continuous visual attention or manual operation.

The study will employ virtual reality (VR) to simulate the layout of the Cubicus building. Participants will wear VR headsets to navigate through the simulated environment while receiving tactile guidance from the fake phone. The device will be positioned in different locations, on the participant's leg, chest, or in their hand, to evaluate the impact of placement on navigation performance. Across multiple trials, the escape route's complexity will be adjusted to test participants' ability to follow the cues under varying conditions. The research will focus on measuring evacuation speed, response accuracy to tactile signals, and the influence of confidence levels on performance outcomes.

Some individuals may feel discomfort, such as nausea or dizziness, while using a VR headset. If you experience any such symptoms, please notify the researcher immediately. You can withdraw from this study at any point, without needing to provide a reason and without facing any consequences.

All collected data will be treated confidentially and anonymized to protect your privacy. Anonymized data from this study may be shared with other researchers if the findings are published in a research report. The anonymized data will be stored until the publication of the research report.

If you have any additional questions, please feel free to reach out to the researchers conducting the study or the supervising advisor.

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I have read and understood the study information dated 19.02.2025, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction. Yes No

I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions, and I can withdraw from the study at any time, without having to give a reason. Yes No

I understand that taking part in the study involves the following risks: The use of a VR-headset may evoke sickness and/or nausea. Yes No

I understand that the information I provide will be used for a Bachelor´s thesis and potential research paper. Yes No

I understand that personal information collected about me that can identify me, such as age, gender or nationality will be completely anonymized. Yes No

I understand that my anonymized data may be shared with other researchers in the process of publication. Yes No

Appendix D
Cuicus knowledge

Are you or have you been a student or staff member at the University of Twente?

Yes No

For how long have you been at the University of Twente?

Less than 1 year 1-2 years

2-3 years

More than 3 years

Have you ever been inside of the Cubicus?

Yes No

On average, how often did you visit the Cubicus building during a semester before the renovation?

Almost never

Once a week

Multiple times a week

Daily

How confident are you to find a random room in the Cubicus?

From 0 to 100

Did you ever get lost while trying to find a room in the Cubicus?

Never

Sometimes

Often

If you got lost or think the Cubicus is a confusing building: Why?