Effect of the sound environment on spatial knowledge acquisition in a virtual outpatient polyclinic

Abstract: This study examines the impact of the sound environment on spatial knowledge acquisition in a virtual outpatient polyclinic. Outpatient polyclinics have a salient role in determining early outpatient treatments of COVID-19 to prevent hospitalization or death and reduce the burden on hospitals. However, they have not been widely investigated in the literature. The studies on spatial knowledge have identified environmental elements mainly related to vision with no focus on sound. Currently, there is limited research on the effect of sound environment on spatial knowledge acquisition in virtual outpatient polyclinics. In this study, a virtual simulated outpatient polyclinic has been created with varying levels of visual and audio cues. Eighty participants were randomly assigned to one of the four groups: a control (no visual signage), a visual (visual signage), an only audio (no landmarks and no visual signage), and an audio-visual group. The virtual environment was presented as a video walkthrough with passive exploration to test spatial knowledge acquisition with tasks based on the landmark-route-survey model. The results showed that a combination of visual signage and sound environment resulted in higher spatial knowledge acquisition. No significant difference was found between the performance of the visual group and the control group that shows that signage alone cannot aid spatial knowledge in virtual outpatient polyclinics. Data from the only audio group suggests that landmarks associated with sound can compensate for the lack of visual landmarks that can help design a wayfinding system for users with visual disabilities.

Keywords: Landmark-route-survey model; Outpatient polyclinics; Sound environment; Spatial knowledge; Virtual environments

1. Introduction

Spatial knowledge development is one of the four theories of wayfinding (Jamshidi & Pati, 2021). Human spatial knowledge is linked to and defined by finding and following routes from one destination to another (Kuipers, 1990). Hospitals are among the most complex environments that the public accesses (Zijlstra et al., 2016). Better acquisition of spatial knowledge in hospitals leads to better wayfinding performance (Gärling et al., 1981; Siegel & White, 1975) that benefits patients, institutions, and medical outcomes (Rodrigues et al., 2020). It reduces lost staff and patient time and users' dissatisfaction because of being disoriented, enhances staff concentration for not being interrupted to provide directions, and minimizes the costs of delayed or missed appointments. In hospitals and other healthcare units, wayfinding is generally emergency with patients or visitors aiming to find their destination as quickly as possible, either for an appointment or finding the emergency unit, or visiting a patient (Greenroyd et al., 2018). In this process, unfamiliarity with the setting and crowdedness puts the visitors in a stressful situation as they try to navigate and find their way within the space (Baskaya et al., 2004). In the case of outpatient polyclinics, complex floor layouts make wayfinding daunting for familiar and unfamiliar users. Navigating between diagnosis and analysis units of an outpatient polyclinic can be difficult because of poor signage, poor layout design and crowdedness (Baskaya et al., 2004). Being disoriented or uncertain of one's location can cause anxiety and distress in unfamiliar spaces (Gibson, 2009). This has gained even more importance with the outbreak of the COVID-19 virus and the increased anxiety and stress levels in healthcare units (Hau et al., 2020).

Acquisition of spatial knowledge is a cognitive process involved in locating targets, estimating distance and directional associations, and perceiving objects' orientation and position (Lawton, 2010). The landmark-Route-Survey (LRS) model of spatial knowledge, described by Siegel and White (1975), is still among the most accepted theories of spatial representation. Landmark knowledge refers to the identity of places (landmarks) and objects based on their salience, appearances, and subjective importance without knowing their relative spatial relationship (Iachini et al., 2009). It requires the acquisition of sensory and semantic information, storage of the representation in long-term memory, and the retrieval of the memory when prompted (Parong et al., 2020). Route knowledge connects the landmarks that are necessary to reach one point from another (Siegel & White, 1975). Survey knowledge (or configurational knowledge) is knowledge of the spatial layout and spatial relationships between objects and places. Survey knowledge demands the acquisition, storage, and retrieval of landmarks and routes and their orientations from long-term and working memory. Successful wayfinding requires all three types of spatial knowledge. A variety of tasks have been used to measure spatial knowledge such as cue recognition, object recall, pointing task, scene recognition task (Carassa et al., 2002), route drawing (Iaria et al., 2009), chronological scene classification, and sketch-mapping tasks (Gaunet et al., 2001; Lapeyre et al., 2011).

Wayfinding is the real-world application of spatial knowledge that corresponds with spatial abilities such as spatial perception and mental rotation (Choi et al., 2006). Wayfinding relies on environmental cues such as landmarks and signage (spatial cues such as arrows, color coding, and directional texts) (Morag & Pintelon, 2021; Rodrigues et al., 2020). However, this system can be confusing because of the hospitals' complex layouts and the overwhelming number of signs (Passini, 1984). Plan configuration, spatial landmarks, spatial differentiation, signage, and room numbers are cited as the factors that aid wayfinding (Weisman, 1981). Although these environmental cues ease wayfinding, there are also difficulties related to their use, such as highly reflective decorative elements, misleading lighting, and signage size and placement (Rousek & Hallbeck, 2011). Studies conducted on the use of signage as wayfinding aids suggest that signage alone cannot overcome architectural failures (Arthur & Passini, 1992), furthermore, increasing the number of signage has been found to decrease wayfinding performance (Carpman, 1984). Even well-designed signs may not provide enough cues for efficient wayfinding (Lee et al., 2014; Rousek & Hallbeck, 2011). The problems associated with the use of visual environmental cues exacerbate with visual impairment and cognitive decline associated with aging (Bosch & Gharaveis, 2017). Thus, in recent years, there has been a growing emphasis on the use of alternative methods such as digital wayfinding systems (Morag & Pintelon, 2021) and the use of auditory and haptic cues for all users, especially in spaces with a proliferation of visual signage (Devlin, 2014). Spatialized sounds emitted from specific decision points or landmarks are also among methods proposed by the literature (Bosch & Gharaveis, 2017). Although there has been developments in information and communication equipment, accessible wayfinding is still hard to achieve for the blind and partially sighted (Chandler & Worsfold, 2013).

The attention devoted to spatial learning is among the factors that determine the successful acquisition of spatial knowledge (Albert et al., 1999). In the last 30 years, there has been a great deal of research on the automatic capture of spatial attention following the presentation of spatially nonpredictive cues (Spence & Santangelo, 2009). While the majority of the work has focused on the capture of spatial attention by visual cues (Wright & Ward, 1994, 2008), an increasing number of studies have started to investigate the attention-capturing properties of auditory cues (Ho & Spence, 2005; Spence & Driver, 1994). Research on crossmodal links in spatial attention indicates that the presentation of a cue from different modalities (e.g., vision and hearing) from the same spatial location facilitates spatial attention (Spence et al., 2004). Perception of space relies on integrating information from different modalities (Driver & Spence, 1998). Based on crossmodal links between different modalities, sudden sounds attract not only auditory attention but also visual and tactile attention to their location; likewise, abrupt touches attract auditory and visual attention towards them (Driver & Spence, 1998). Furthermore, recent studies suggest that sound has a leading effect on visual elements' noticeability in a way that variations in sound level correspond with changes in visual attention (Liu et al., 2020).

Regarding the importance of visual elements in acquiring spatial knowledge, it should be noted that visual reference points (e.g., church) are characterized by sound signals (e.g., church bells) (Karimpur & Hamburger, 2016). Thus, pairing visual cues with audio cues may help spatial knowledge acquisition. Designers of virtual worlds utilize various visual and auditory cues to draw attention towards a point of interest or a spatial goal. Nonverbal audio and spatial placement of audio in virtual spaces have been used as navigational cues in prior studies (Burkins & Kopper, 2015; Dodiya & Alexandrov, 2008; Lokki & Grohn, 2005; McMullen & Wakefield, 2014). Lokki and Grohn (2005) explored the use of audio and visual cues in a 3D virtual environment and found that audio cues were as helpful as visual cues. In another virtual environment, Burkins and Kopper (2015) investigated the effect of 3D sound as a wayfinding tool. They found that participants were faster in finding the correct target and had a higher performance in pointing tasks in the maze with audio cues. Hamburger and Röser (2014) compared recognition and wayfinding performance for verbal, visual, and acoustic landmarks (animal sounds) in a virtual environment and found a good recognition and wayfinding performance for acoustic landmarks. Another study found that an interactive exploration in a virtual environment with environmental sound provided sufficient spatial mental maps (Picinali et al., 2014). Marples et al. (2020) explored the effect of landmark, auditory, and illumination cues on player navigation in virtual mazes. The findings indicated that both lighting and audio cues reduced solve time when used in isolation;

however, no reinforcement interaction was detected when they were used together. In another study, instead of using auditory cues, Chandrasekera et al. (2015) investigated the use of soundscape as auditory landmarks in wayfinding tasks. They found that soundscape provided navigation aids and enhanced immersion in virtual environments. In their study, a church, a market place, and a school soundscape were used in a virtual maze as auditory landmarks. Based on the studies mentioned above, it can be concluded that the addition of audio cues in a virtual environment would lead to better performance in spatial knowledge tasks.

As can be seen in the mentioned studies, virtual environments are widely used in answering questions about spatial cognitive processes (Memikoğlu & Demirkan, 2020; Tang et al., 2009). Virtual environments provide an accurate representation of real environments (Westerdahl et al., 2006) while allowing systematic environmental manipulations that cannot be easily implemented in real environments (Kuliga et al., 2015). To achieve environmental comparability, it is vital to simulate naturalistic experiences in virtual environments (Bell et al., 2001). Sketches, photographs, and slide shows are traditional approaches to achieve ecological validity in virtual environments (Bateson & Hui, 1992). Desktops and laptops are among common presentation devices that produce comparable results with high immersive virtual systems (Kalff & Strube, 2011; Kuliga et al., 2015) because they provide sufficient visual realism in spatial knowledge tasks (Green & Jacob, 1991; Parong et al., 2020; Sayers, 2004). It has also been stated that more immersive systems may lead to less behavioral realism because of the difficulties with controls. Virtual environments can be explored either passively or actively (Chrastil & Warren, 2013). A passive exploration model is recommended for indoor public spaces with predetermined routes (Cao et al., 2019).

Theoretical framework

The sound environment contains different sounds simultaneously (Raimbault & Dubois, 2005). Some of these sounds may attract the listener's attention more than others based on the physical characteristic of the signals and the meanings they carry (Papadopoulos et al., 2012). The sound environment of hospitals is generally described as chaotic and noisy

(Löf et al., 2006), with high levels that fluctuate over time (Johansson et al., 2012), populated by speech and a variety of mechanical noises such as paging systems, floor cleaners, beeping alarms and air-conditioning systems (Ryherd et al., 2008). Through an exploratory study, the effect of the available sound sources in an outpatient polyclinic on spatial knowledge acquisition when combined with visual signage were investigated. The logic behind this is based on the findings on multisensory representation, characteristics of auditory attention, and auditory input processing. Multisensory representation suggests that a congruent appearance (in terms of time, location, and meaning) of sound stimuli with a visual target leads to better attention, perception, and memory because of providing more detail in comparison to unisensory presentations (Lehmann & Murray, 2005; Spence et al., 2004; Talsma et al., 2010; Werkhoven et al., 2014). Furthermore, the representation of sound objects in memory is more long-lasting than visual objects. Additionally, auditory input processing occurs earlier than visual input processing (Zimmermann et al., 2016).

The information from different modalities is stored and processed in the working memory before being sent to long-term memory (Baddeley, 1992). The working memory comprises a visuospatial sketch pad, a central executive, and a phonological loop. The phonological loop holds speech-based and acoustic information while the visuospatial sketch pad processes visual and spatial information. In this sense, audio information provided by the sound environment of the outpatient polyclinic would be processed in the phonological loop, while the visual information would be processed in the visuospatial sketchpad. In that sense, if one of the modalities fails to encode or retrieve information, the second may still be successful (Butler et al., 2011).

Previous research has shown that visual and spatial components of working memory are involved in acquiring landmark, route, and survey knowledge (Wen et al., 2011). Here, the aim was to assess whether receiving information from two different modalities (visual and audio) would aid the acquisition of spatial knowledge. Although the literature has stated the benefits of multisensory presentations on attention and memory, there are limited studies that have focused on the effect of multisensory presentations on spatial knowledge. The available ones have only looked at the effect of multisensory presentations on wayfinding and not on spatial knowledge tasks. With this gap in mind, the theoretical framework of the study presented in figure 1 was prepared. Based on this framework, the context provides environmental stimuli that can be visual, auditory, or tactile. The information from these modalities results in auditory and visual memory representations that are assessed independently. The phonological loop processes auditory information while visuospatial information is processed by the visuospatial sketchpad (Baddeley, 1992). These components of working memory lead to landmark, route, and survey knowledge that induce spatial knowledge acquisition (Wen et al., 2011). Within this context, it was hypothesized that the sound sources available in the acoustic environment of an outpatient polyclinic would lead to a better spatial knowledge acquisition when combined with visual signage.

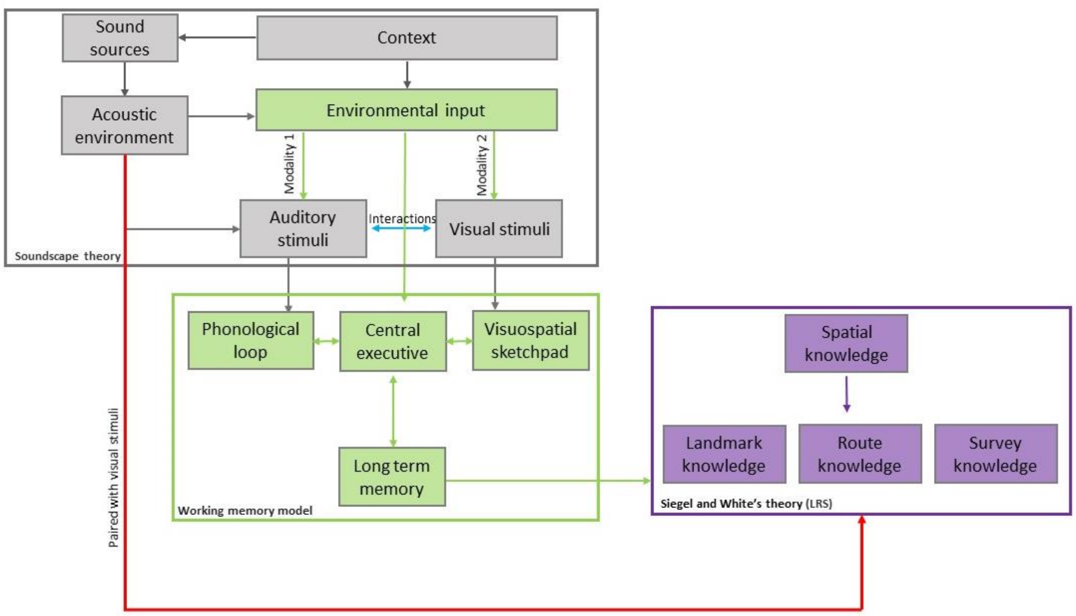


Figure 1. The theoretical framework of the study

What distinguishes this study from others is that while the majority of the studies have been conducted in virtual mazes with animal or object sounds as audio cues, this study has used audio and visual information derived from a real outpatient polyclinic in a simulated virtual environment. The motivation of this study is twofold. First, it aims to contribute to the studies conducted on spatial knowledge by looking at the role of the sound environment. Secondly, it is intended to provide grounds for using the sound environment as a design element to promote spatial knowledge by analyzing the physical and perceptual characteristics of the sound. In that sense, the following research questions are proposed.

Q1: Is there any association between spatial knowledge acquisition among different components (control group, visual group, audio group, audio-visual group)?

Q2: Is there any association between the sound sources and the remembered landmarks in the spatial knowledge tasks?

2. Materials and Methods

2.1. Participants

In this study, a convenience sample of 80 healthy students and employees from Bilkent University, Turkey was used. With statistical power held at 0.80, this sample size was sufficient to detect significant effects. The exclusion criteria were being unfamiliarity with the setting. To prime the participants, they were asked to imagine that they were simulated visitors of the outpatient polyclinic in Bilkent Integrated Health Campus. The participants were randomly divided into four experimental groups that varied in the level of visual (signage) and audio (sound environment) stimuli, with 20 people (10 women and 10 men) in each group. All the participants were informed about the study protocol, voluntarily participated in the study, and filled a written consent form.

The participants' age distribution ranged from 19 to 40 years (mean=27.16 years, SD =4.527). Gender, age, education level, major, and nationality were collected as sample demographic information, shown in Table 1.

Table 1. Demographic characteristics of the participants in each experiment group

	Gender		**Education level**		**Age**		**Department**				**Nationality**		
	F	M	University	Masters /PhD	M	SD	Engineer	Design	Science	Other	Turkish	Iranian	Other
Group 1	10	10	5 25.0%	15 75.0%	28.6	4.97	11 55.0 %	2 10.0%	5 25.0%	2 10.0 %	8 40.0%	9 45.0%	3 15.0 %
Group 2	10	10	2 10.0%	18 90.0%	27.2	3.82	13 65.0%	3 15.0%	0 0	4 20.0 %	7 35.0%	9 45.0%	4 20.0 %

Group 3	10	10	13 65.0%	7 35.0%	24.65	3.93	7 35.0%	5 25.0%	1 5.0%	7 35.0 %	15 75.0%	5 25.0%	0 0
Group 4	10	10	5 25.0%	15 75.0%	28.2	4.51	13 65.0%	5 25.0%	2 10.0%	0 0	9 45.0%	10 50.0%	1 5.0%
Total	40	40	25	55	27.16	4.52	44	15	8	13	39	33	8

2.2. Virtual environment

In this study, the outpatient polyclinic of Bilkent Integrated Health Campus in Ankara was simulated to create a desktop virtual environment with predetermined routes that did not involve active wayfinding tasks. This hospital is the largest city hospital in Turkey (Kerman et al., 2012; Özkan, 2018) and serves as one of the hospitals to treat COVID-19 patients. This outpatient polyclinic has a large area and complex layout that make it a suitable choice for study. Figure 2 presents the schematic plan of the outpatient polyclinic with the traveled route. A detailed description of the visual signage is provided in Appendix D.

Figure 2. The outpatient polyclinic plan shows the entrance, the traveled route, the elevators, the escalators, and the patient administration desks. The interior pictures were taken from 1, 2, and 3.

The real outpatient polyclinic was visited to capture a visual and audio recording of a route starting from the main entrance leading up to the neurology department. A Canon PowerShot G10 equipped with a binaural microphone was used to collect the real environment's visual and audio data. Figure 3 shows interior pictures of the space.

Figure 3. Interior pictures of the real environment showing the escalators, the staircases, and the patient administration desks

Chief Architect Premier X11 was used to create a 3D simulation of the space. The scenes were rendered in real-time at a speed of 20 frames per second (Min & Ha, 2020). A video of the specified route was created by using the Walkthrough path tool for passive exploration. This route was similar to the one that was recorded in the real environment.

Similar to previous virtual environments, the route was shown with a plain ceiling with sufficient contrast between the floor and the walls. No light sources were used to avoid directional cues from shadows (Sharma et al., 2017). The route was made of uniform and undistinguishable paths and neutral-colored walls so that the walls did not provide wayfinding cues (Lingwood et al., 2015). A simple model with grey-scale textures and little detail was preferred to assess users' performance in isolation from other factors as recommended by the literature (Kuliga et al., 2015; Natapov et al., 2015; Von Stulpnagel et al., 2014). Figure 4 presents renderings of the virtual environment.

Figure 4. Interior renders of the simulated virtual environment representing the skylight, the escalators, and patient administration desks

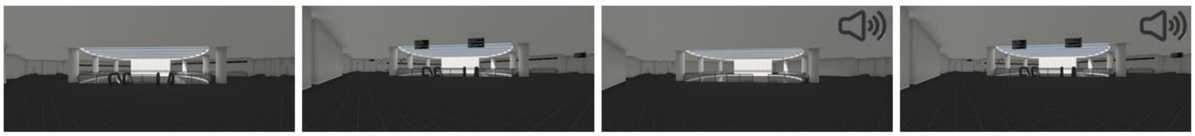
2.3. Experimental Stimuli

Three different videos were created with the walkthrough path tool. One of the videos had the exact visual signage from the real environment. The other one was wiped of all the available signage to create the control group's experiment setting, and the last video was wiped of all the landmarks. The video with the visual signage and the one with no landmarks were reproduced by adding audio to them with Cyberlink PowerDirector editing software. Clapping was used to synchronize the video and sound information. Overall, four different experimental models were created that are:

- Group 1 (control group): No visual and no audio information was provided in the virtual environment.
- Group 2 (visual group): Visual signage was provided in the virtual environment.
- Group 3 (only-audio group): All landmarks and visual signage were removed from the virtual environment. Only the sound environment was available.
- Group 4 (audio-visual group): Visual signage and polyclinic sound environment were provided in the virtual environment.

The models were animated with a wide-angle lens following the route to provide a 65-degree field of view and a more immersive virtual environment (Lee & Kline, 2011). Figure 5 represents screenshots of each experiment group.

Figure 5. Created videos for each experiment group from left to right: Control group, Visual group,



only- audio, and audio-visual group

The simulated eye height was set to 1.60 meters from the floor, and walking speed was a constant of 1.1 m/s (Haq et al., 2005; Lee & Kline, 2011; North, 2002). The video duration was 185 seconds (including stops before the intersections). The route was identical for the different conditions, with a length of 154 meters and eight direction changes (three times left, five times right). A 17-inch Asus personal computer was used (2.59 GHz, 16 Gb RAM with an nVidia GeForce GTX 960) as an apparatus to provide visual information. The laptop was placed on a desk, and the participants sat in a chair approximately 50 cm from the screen. Each participant undertook the test individually and without interruption in the experimenter's office with closed doors and windows. Binaural signals of the soundscape were delivered by computer through headphones (ROG Strix Fusion 300 7.1) (Shu & Ma, 2018).

2.4. Procedure

The scenario of the test was introduced to the participants before the test. Participants were asked to watch a video of a route and recall details such as where to turn and certain architectural elements. A questionnaire (See Appendix A and B) was handed out to each participant before viewing the video. Before watching the video, the participants were asked to answer demographic information about themselves. The participants' hearing was tested with the Widex online hearing test. All the participants had normal hearing. Although there were no sound stimuli in the control group (group 1) and visual group (group 2), all the participants were asked to wear headphones for standardization and to create a feeling of presence (Liu et al., 2020; Marples et al., 2020). After the hearing test and filling in demographic information, the participants watched the video. The video started from the outpatient polyclinic entrance, traveled across the patient admission desks and elevators, and finally arrived at the destination, the neurology department. The plan of the space was not available to the participants during the learning phase. Figure 6 presents a schematic flowchart of the procedure.

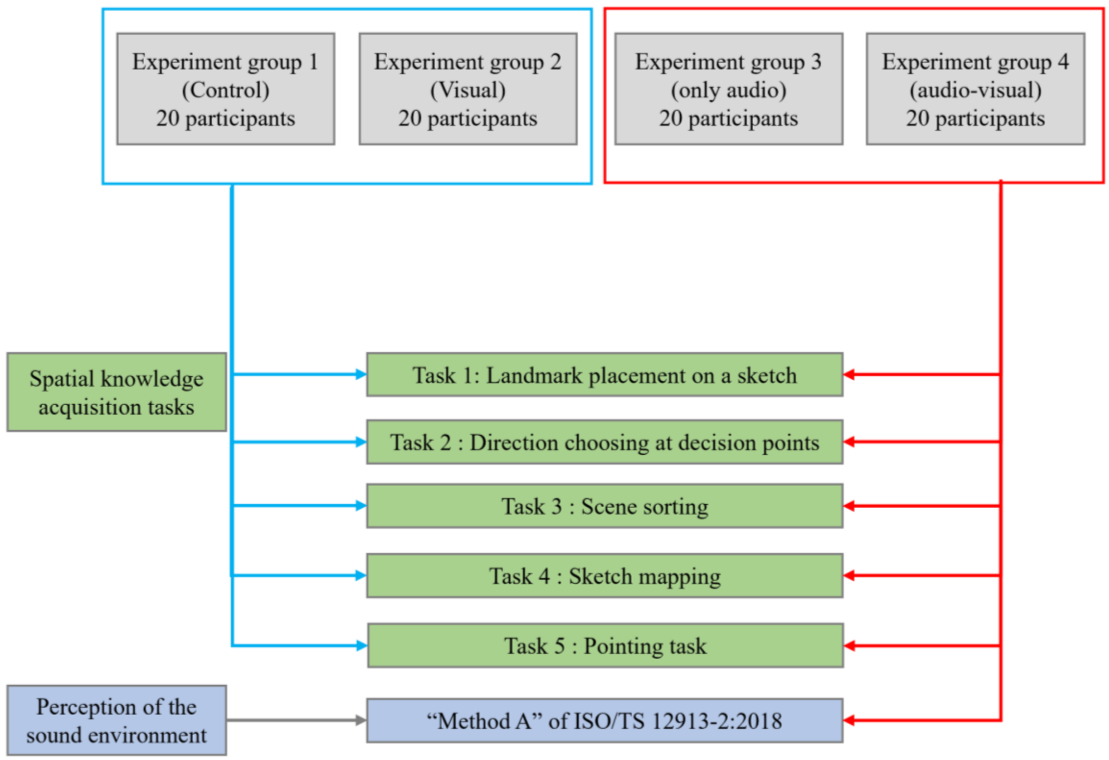


Figure 6. Schematic flowchart of the study

2.5. Performance tasks

After watching the video, all groups were asked to do five different spatial memory tasks using the Landmark-Route-Survey model representation (Cogné et al., 2018). A landmark placement task was used to measure landmark knowledge. In this task, the participants were presented with a schematic plan of the outpatient polyclinic that showed the beginning of the route. They were asked to place the escalator, the staircases, the elevators, and the patient administration desks on the blank plan as accurately as possible similar to previous studies (Meneghetti et al., 2017; Muffato et al., 2017). For scoring purposes, the completed sketch maps were scanned and uploaded each plan to Gardony

Map Drawing Analyzer (GMDA version 1.2) (Gardony et al., 2016). This software is based on a bidimensional regression method (Friedman & Kohler, 2003) and compares the landmarks' location on the map and their Cartesian coordinates previously calculated on the target layout. The program generates several parameters. Like previous studies, the canonical organization's square root (SQRT-CO), ranging from 0 to 1, as a global index of accuracy was considered (Muffato et al., 2017). A higher score indicates a better performance. See the Appendix C for details of the tasks.

A direction choosing and scene sorting task were used to measure route knowledge. For the direction choosing at different decision points, the participants were asked to watch the video again, but this time the video would pause at each decision point, and the participants were asked to choose the correct direction (straight, right, and left) at each point (6 points to choose), on the questionnaire. Feedback was provided to the participants after answering each question, similar to previous studies (Muffato et al., 2020). Percentages of correctly taken directions were considered for scoring purposes similar to previous studies (Wen et al., 2011). In the scene sorting task, the participants were presented with eight pictures taken along the route and asked them to sort them chronologically, similar to previous studies (Wallet et al., 2011). In this task, the sorting errors were counted. This score was then compared to the best possible score (i.e., 8) to obtain percentages.

A sketch mapping and a pointing task were used to measure survey knowledge. In the sketch-mapping task, the participants were presented with the plan showing the escalators' location, the staircases, and other architectural elements and asked them to draw the route they had watched on the video (Wallet et al., 2011). A pass or fail method was used to analyze the data (Cogné et al., 2018). In the pointing task, the participants were asked to imagine standing at a given landmark, facing another, and pointing to a third (Muffato et al., 2017). For scoring purposes, the circular mean of the minimum angles between each participant's response and the correct direction (0–180°) was considered (Borella et al., 2015; Muffato et al., 2017). The final pointing score consisted of the mean error score for the four pointing tasks.

Additionally, the participants in groups 3 and 4 filled in "Method A" of ISO/TS 12913-2:2018 questionnaire on the sound environment (Acun & Yilmazer, 2018, 2019; ISO, 2018; Orhan & Yilmazer, 2021). The first part of the questionnaire classifies the sound sources into four categories: traffic noises, other sounds, sounds from human beings, and natural sounds on a scale from “1-not at all to 5-dominates completely”. The second part examines the sound environment's perceived affective quality based on eight perceptual attributes (pleasant, chaotic, vibrant, uneventful, calm, annoying, eventful, and monotonous) on a scale from “1-strongly disagree to 5-strongly agree”. The perceived affective quality is based on a two-dimensional model proposed by Axelsson et al. (2010). This modal is defined by four bipolar factors: the two orthogonal factors, Pleasantness and Eventfulness, which are located at a 45° (degrees) rotation from the second set of orthogonal factors, Calmness, and Excitement. According to this model, an exciting soundscape is pleasant and eventful, whereas a calm soundscape is pleasant and uneventful. In the same way, a chaotic soundscape is unpleasant and eventful, whereas a monotonous soundscape is unpleasant and uneventful. The data is generally presented on a radar graph to demonstrate the association between the attributes based on each attributes’ mean score. The third part of the questionnaire assesses the sound environment on a scale from 1-very bad to 5-very good, and the fourth part analyzes the appropriateness of the sound environment on a scale from 1-not at all to 5-perfectly.

2.6. Data Analysis

The Statistical Package for the Social Sciences (SPSS 25.0, IBM, USA) was used to analyze the data. All tasks showed good internal reliability (Cronbach’s α from 0.70 to 0.88). Leven’s test in all tasks indicated homogeneity of variance; thus, parametric tests were used to analyze the data. A one-way ANOVA was used to analyze the data between the groups in all tasks except the sketch mapping task. A Scheffe Test was used as a post-hoc test to make pairwise comparisons between the groups. In the sketch mapping task, since the data was categorical (fail or pass), a chi-square test was used to make pairwise comparisons between the groups.

3. Results

3.1. Spatial knowledge performances in each task

Task 1 (Landmark placement on a sketch) analysis: The results indicated a significant difference between the subjects' performance; F (3,76) = 17.037, p < 0.001, η2 = 0.402 (observed power = 1.000). Scheffe Post Hoc Test was applied to compare performance in a pairwise fashion. There was a significant difference between group 1 and group 4, p<0.001, and between group 2 and group 4, p<0.001, and between group 3 and 4, p<0.001; however, there was no significant difference between group 1 and group 2 (p=1.000), group 1 and 3 (p=0.138), and 2 and 3 (p=0.149). The participant in group 4 scored higher (mean score=0.777) than group 2 (mean score=0.497), group 1 (mean score=0.499) and group 3 (mean score=0.355). See Figure 7 for the representation of the data analysis between the experiment groups in task 1. Crosstabs were also prepared on the association between the remembered landmarks and the experiment groups, as seen in table 2.

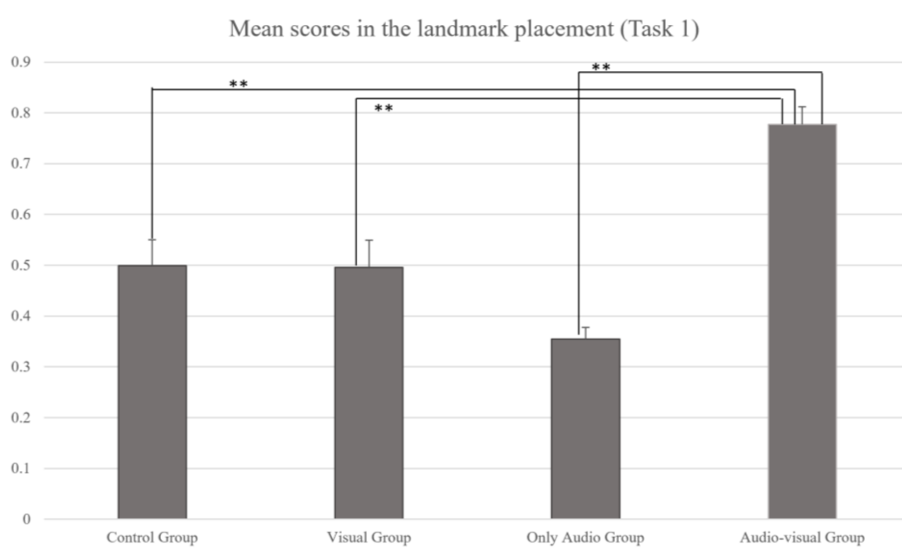


Figure 7. Mean scores in the landmark placement (Task 1) across the experiment groups. Each panel displays performance for the control, visual group, only-audio group, audio-visual group conditions. Significant differences are indicated by asterisks that denote a significance level of $p < .05$

	Escalator	Admission 1	Admission 2	Elevator 1	Elevator 2	Staircase

	0	1	0	1	0	1	0	1	0	1	0	1
Group 1	2 10.0%	18 90.0 %	12 60.0 %	8 40.0%	12 60.0%	8 40.0%	13 65.0 %	7 35.0 %	18 90.0 %	2 10.0%	9 45.0%	11 55.0%
Group 2	4 20.0%	16 80.0 %	7 35.0 %	13 65.0 %	12 60.0%	8 40.0%	10 50.0%	10 50.0%	19 95.0%	1 5.0%	11 55.0%	9 45.0%
Group 3	5 25.0 %	15 75.0%	14 70.0%	6 30.0 %	20 100.0 %	0 0.0%	14 70.0%	6 30.0 %	20 100.0%	0 0.0%	20 100.0 %	0 0.0%
Group 4	0 0.0 %	20 100.0%	3 15.0%	17 85.0%	7 35.0%	13 65.0%	2 10.0%	18 90.0 %	11 55.0%	9 45.0%	8 40.0%	12 60.0%
Total	11 13.8%	69 86.3%	36 45.0%	44 55.0%	51 63.7%	29 36.3%	39 48.8%	41 51.2%	68 85.0%	12 15.0%	48 60.0%	32 40.0%

Table 2. Association between the remembered landmarks and the experiment groups.

In the landmark placement task, the escalators were correctly placed on the plan by at least 75% of the participants in all groups. The first admission desk was missed by at least 60% of the participants in the control and only audio group, while more than 65% of the participants in the visual and audio-visual group placed it correctly on the plan. In the case of the visitor's elevator (elevator 1), more than half of the participants in group 1 missed this landmark while 50% of the participants in the visual group placed it correctly. The interesting point is that 70% of the participants in the only audio group had placed the visitor's elevator correctly on the plan. In the audio-visual group 90% of the participants placed the elevators correctly. The second elevators were missed by more than 90% of the participants in group 1, 2 and 3 while 55% of the participants in the audio-visual group remembered it correctly. The second admission desk was missed by 60% of the participants in group 1 and 2 and all the participants in the only audio group. 65% of the participants in the audio-visual had placed it correctly. The staircase was missed by 45% and 55% of the participants in group 1 and 2 respectively. All the participants in the only audio group had missed the staircase while 60% of the participants in the audio-visual group had remembered it correctly.

Task 2 (Direction choosing at decision points) analysis: Comparison of the percentages of correct answers showed a significant difference between the groups in this task. $F (3,76) = 3.843$, $p = 0.013$, $\eta 2 = 0.131$ (observed power=0.802). Scheffe Post Hoc Test was applied to compare performance in a pairwise fashion. There was a significant difference between group 1 and group 4, p=0.022. There was no significant difference between group 1 and group 2 (p=0.391), group 1 and 3 (p=0.913), 2 and 3 (p=0.792), 2 and 4 (p=0.553), and 3 and 4 (p=0.115). The bar graph shows the mean scores in group 4 (mean score=95.832), group 2 (mean score=87.49), group 3 (mean score =81.64), and group 1 (mean score=77.94). Figure 8 presents the mean scores across all four groups.

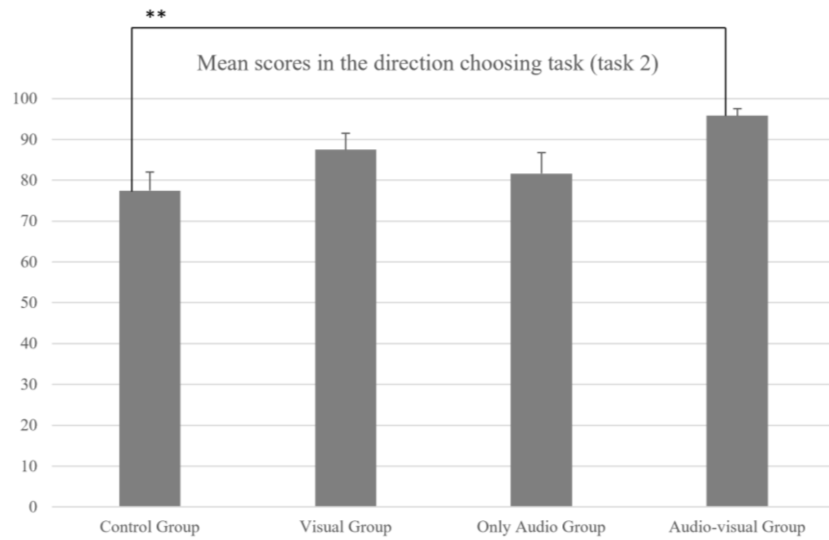


Figure 8. Mean scores in direction choosing (Task 2) across the experiment groups. Each panel displays performance for the control, visual group, only-audio and audio-visual group. Significant differences are indicated by asterisks that denote a significance level of $p < .05$

Task 3 (Sorting task) analysis: Comparisons of percentages of correctly ordered pictures indicated a significant effect of the experiment group on performance; $F(3,76) = 5.183$, $p= 0.003$, $\eta2 = 0.170$ (observed power= 0.912). Scheffe post hoc test indicated a difference between group 1 and group 4 (p=0.009) and group 2 and group 4 (p=0.026). No difference was detected between group 1 and group 2 (p=0.984), 1 and 3 (p=0.299), 2 and 3 (p=0.507), and 3 and 4 (p=0.469). The bar graph shows that participants in group 4 (mean score=86.875) performed better than group 3 (mean score=71.87), group 2 (mean score =57.50), and group 1 (mean score=53.75). Figure 9 represents the data distribution in task 3 across the groups.

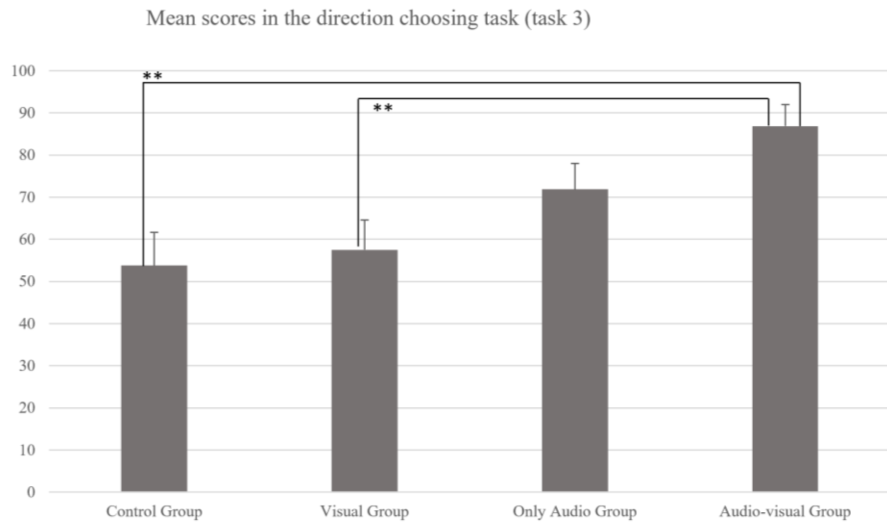


Figure 9. Mean scores in the sorting task (Task 3) across the experiment groups. Each panel displays performance for the control, visual group, only-audio and audio-visual group. Significant differences are indicated by asterisks that denote a significance level of $p < .05$

Task 4 (Sketch-mapping) analysis: In this task, the aim was to analyze whether the experiment group had any impact on passing or failing drawing the sketch map. Since the data were categorical, a Chi-square test was used to analyze the data. Results showed a significant difference between the groups, $X^2 = 13.759$, p=0.003. Z scores were compared to see where the significance existed; p-values were adjusted with the Bonferroni method to avoid type 1 error (Beasley & Schumacker, 1995). The results suggested a significant difference between passed or failed sketch maps in group 1 and group 4 (X2=12.379, P<0.001), 2 and 4 (X2=8.640, p=0.003), 3 and 4 (X2=5.584, p=0.018). However, no difference existed between groups 1 and 2 (X2=0.440, P=0.507), 1 and 3 (X2=1.667, p=0.197), 2 and 3 (X2=0.404, p=0.525) in the proportion of passed or failed drawn sketch maps. The percentages of the correct answers within each group were compared. 30.0% in group 1, 40.0% in group 2, 50% in group 3, and 85.0% of the participants in group 4 successfully drew the sketch mapping task. Table 3 presents the percentages of the correct and the wrong sketch maps.

Table 3. Number and percentages of correct and wrong sketch-maps (Task 4) across the groups

	Control group	**Visual group**	**Only-Audio group**	**Audio-visual group**
Wrong	14	12	10	3
Within Groups	70.0%	60.0%	50.0%	15.0%
Correct	6	8	10	17
Within Groups	30.0%	40.0%	50.0%	85.0%

Task 5 (Pointing task) analysis: The results indicated a significant effect of experiment group on performance; $F(3,76) = 13.285$, $p<0.001$, $\eta 2 = 0.344$ (observed power=1.000). Scheffe test indicated a significant difference between group 1 and group 2 ($p=0.026$), between group 1 and group 3 ($p<0.001$), 1 and 4 ($p<0.001$), and 2 and 4 ($p=0.041$). There was no significant difference between groups 2 and 3 ($p=0.613$), and 3 and 4 ($p=0.470$). The average deviation from the correct direction was the lowest for group 4 with 17.99 degrees, followed by group 3 with 37.62 degrees and group 2 with a 54.18-degree deviation. Group 1 had the worst performance with a 92.60-degree deviation. Figure 10 represents the data analysis in the pointing task.

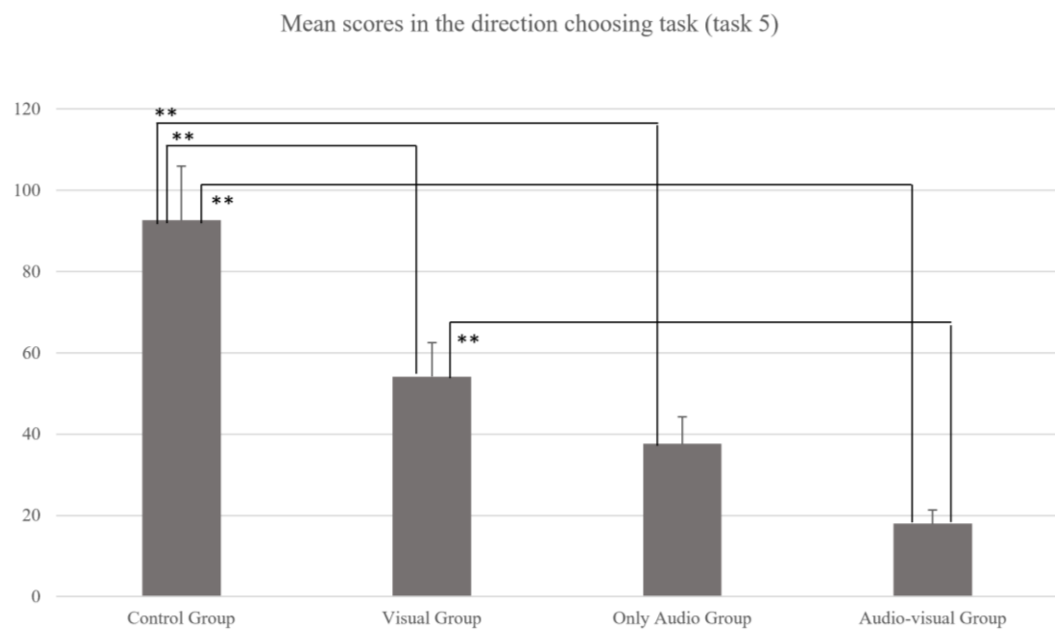


Figure 10. Mean scores in the pointing task (Task 5) across the experiment groups. Each panel displays performance for the control, visual, only-audio, and audio-visual conditions. Significant differences are indicated by asterisks that denote a significance level of $p < .05$

Overall, the results indicate a significant effect of the experiment group on acquiring spatial knowledge. Table 3 summarizes the ANOVA results and mean scores of the tasks across the experiment groups.

Table 3. Summary of ANOVA and mean scores across all tasks

Tasks	df	F	p	Experiment Groups	Scores
Landmark placement	3	17.037	p<0.001	Control group	0.499
				Visual group	0.497
				Only audio group	0.355
				Audio-visual group	0.777

Direction choosing	3	3.843	0.01	Control group	77.94
				Visual group	87.49
				Only audio group	81.64
				Audio-visual group	95.83
Scene sorting	3	5.183	0.003	Control group	53.75
				Visual group	57.50
				Only audio group	71.87
				Audio-visual group	86.87
Sketch mapping	3	13.759 [a]	0.003	Control group	30 [b]
				Visual group	40
				Only audio group	50
				Audio-visual group	55
Pointing task	3	13.285	p<0.001	Control group	92.60
				Visual group	54.18
				Only audio group	37.62
				Audio-visual group	17.99

[a] X^2 values have been reported here.
[b] is the percentages of correctly drawn sketch maps.

3.2. Perceptual analysis of the sound environment

To understand participants' perception of the overall sound environment, the participants in groups 3 and 4 were asked to watch the video again and fill in Method A of the ISO/TS 12913-2:2018 (ISO, 2018) questionnaire after finishing the spatial knowledge tasks. Figure 11 shows the categories of the sounds heard by the participants in both groups. Human sounds were the dominant sounds in both groups.

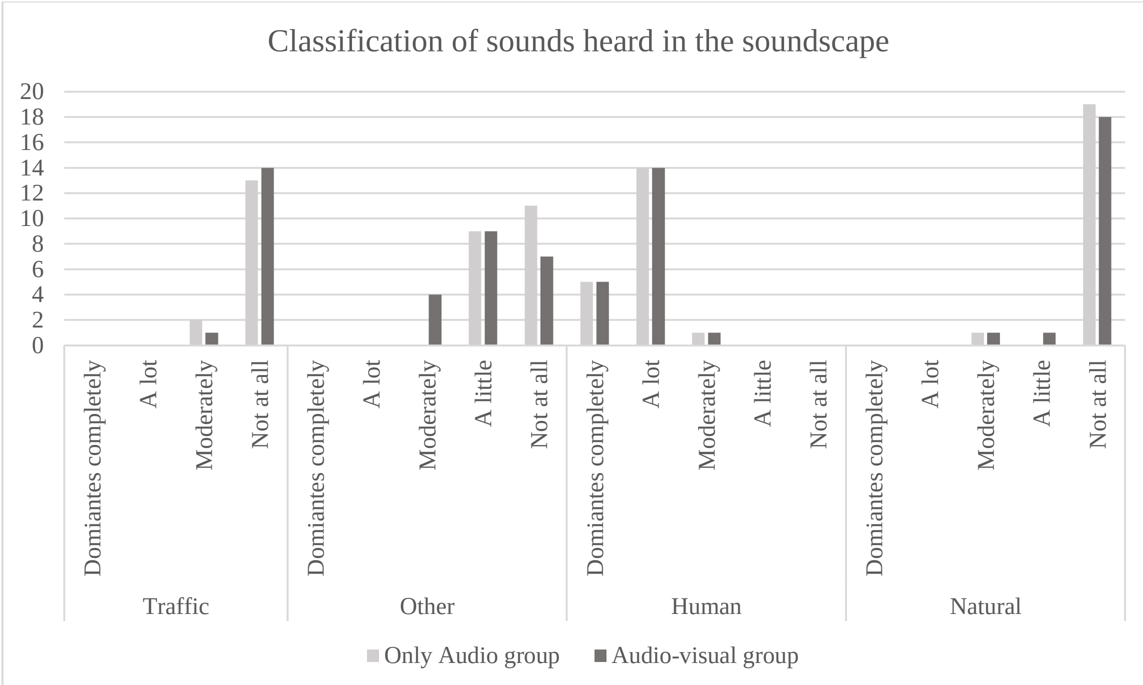


Figure 11. Classification of sounds heard in the soundscape

The radar graph presented in figure 12 shows the participants' perception towards the sound environment through two orthogonal components of valence (annoying-pleasant) and activation (uneventful-eventful). Any perceptual outcome in the pleasant region is a positive sound environment (pleasant, calm, vibrant), while outcomes located in the annoying region make up a negative sound environment. The emotional assessment of the sound environment shows convergence towards the eventful-chaotic-annoying region that presents a negative sound environment.

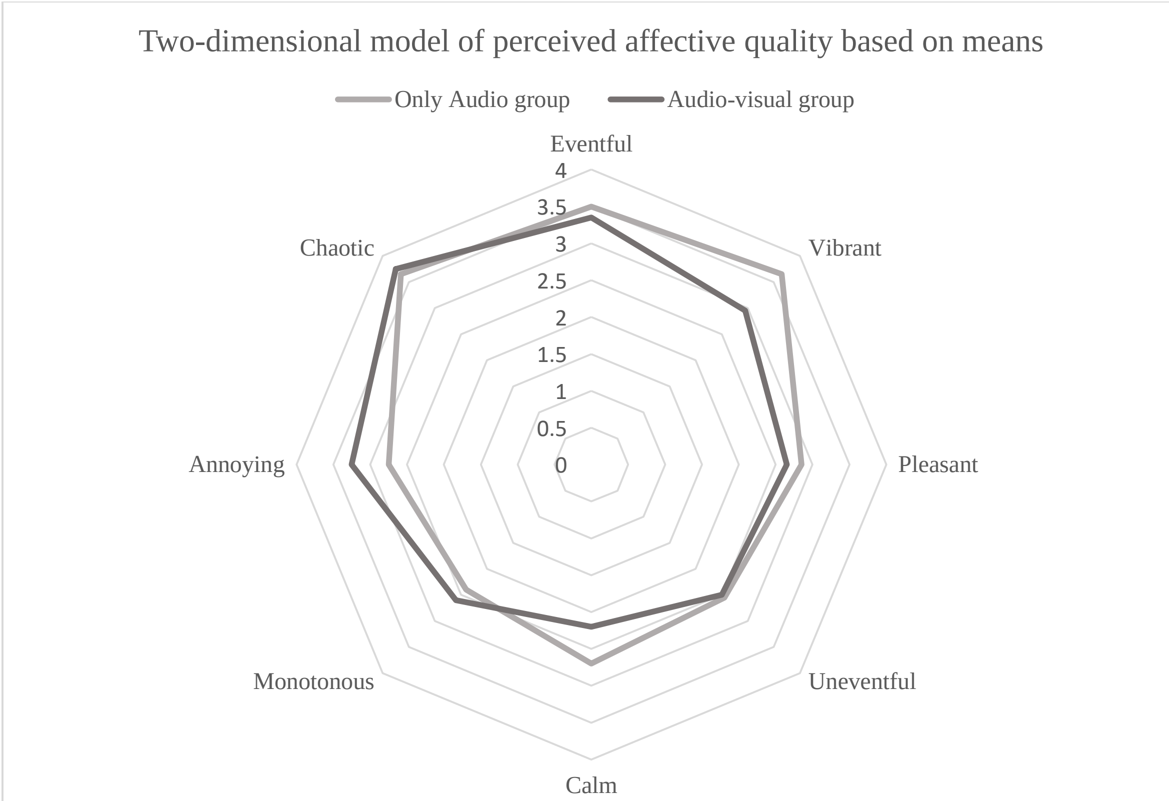


Figure 12. Two-dimensional model of perceived affective quality based on means

Figure 13 and figure 14 present participants' assessment of the sound environment and its appropriateness, respectively. The majority of the participants in group 3 rated the sound environment as neither good nor bad, while the majority of the participants in group 4 rated it as good. In terms of the sound environments' appropriateness, the majority of the participants in both groups rated it as either moderate or very much.

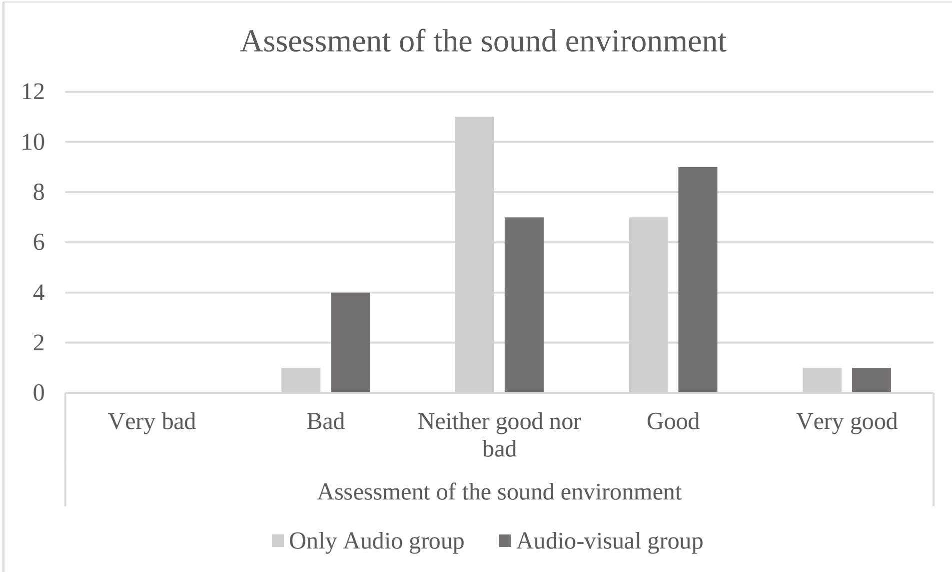


Figure 13. Assessment of the sound environment

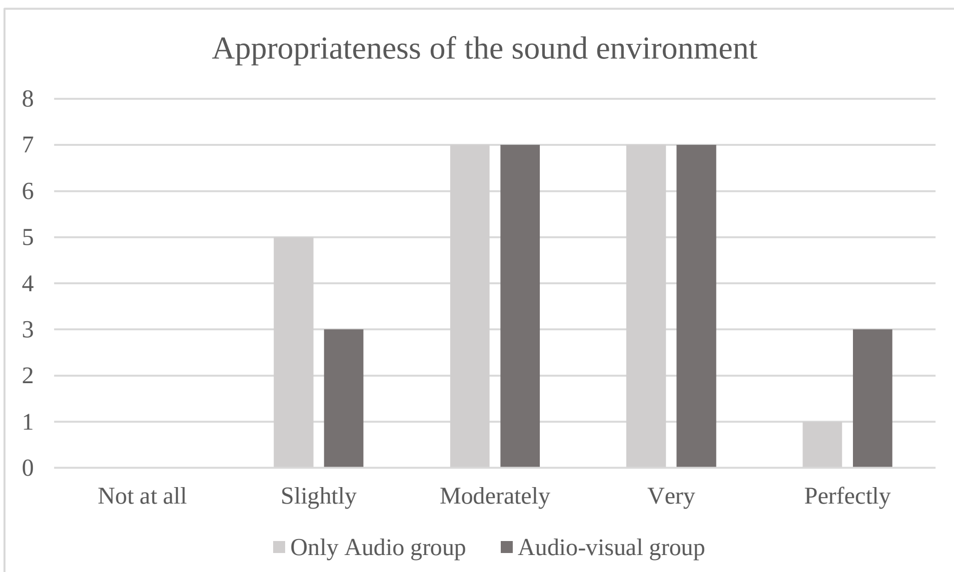


Figure 14. Appropriateness of the sound environment

3.3. Physical analysis of the sound environment

This section discusses the role of the sound environment and its mechanism on how it may have promoted spatial knowledge by analyzing the recorded sound's content. To provide an empirical analysis of the sound environment, a detailed time-frequency analysis, not limited to temporal ones, was conducted, depicted in Fig.15. The spectrogram reveals the changes in the frequency content of the signal over time. The Fourier coefficient of each time-frequency pixel has been encoded in color in which the dark red and blue indicate two extremes of high and low coefficient amplitude, respectively. Based on this time-frequency content, the spectrogram has been divided into several temporal segments indicated by dashed red vertical red lines. The first segment (0-31s) is a temporal portion of the signal from the entrance to the escalators, which shows specific high-frequency content around 400 Hz with a wide bandwidth. The second segment (31s-75s) has a different time-frequency pattern indicating less prominent high-frequency content. This part of the route is from the escalators to the beginning of the patient admission desks. The third segment (75s-92s) has lower frequency variations and less prominent features in the frequency content that matches the acoustic experience of the participants along the patient administration desks. In the next segment (92s-132s), the elevator area has unique tones, which can be seen as short-term bursts around frequencies 0.5kHz and 1.2kHz. The fifth segment (132s-156s) indicates the transient time from the elevator area toward the neurology department entrance, which has distinct patterns than previous ones. This segment has a low amplitude auditory event and is generally quieter than previous segments. The final segment (156s-185s) has distinct frequency content and patterns in low and mid frequency levels along the neurology department. If the analyzed segments are matched to the route's video, it can be seen that each sound segment has taken place in a different space of the outpatient polyclinic. A change in the sound environment's content takes place with a change in the route's direction. The change in amplitude and frequency of the sound environment along the route may have attracted the participants' attention towards the route and other visual elements, resulting in better performance in the spatial knowledge task.

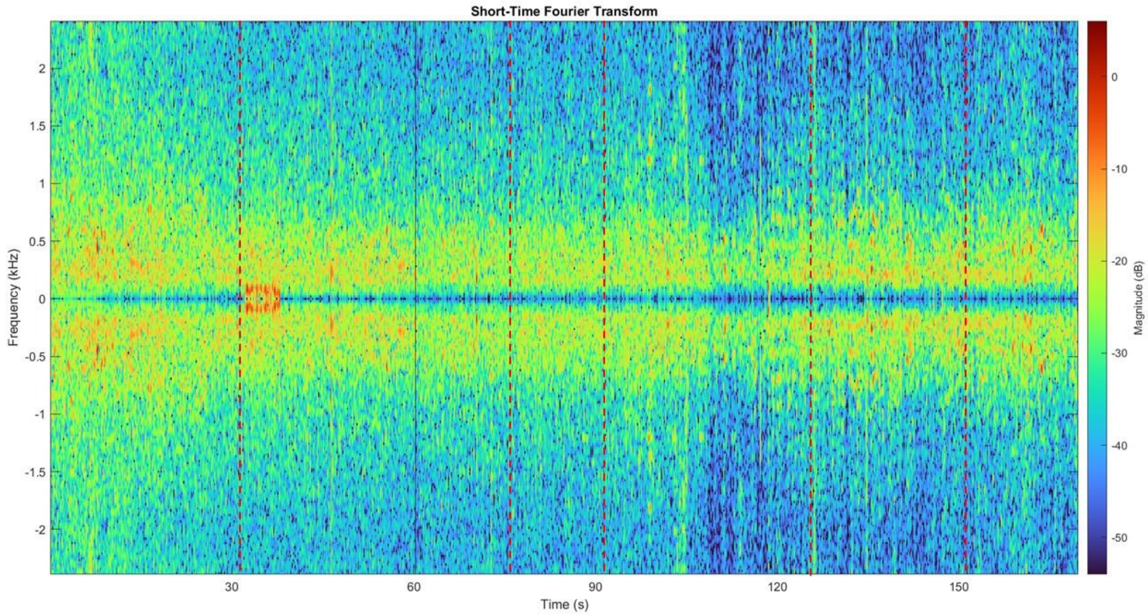


Figure 15. Short-time frequency transform (STFT) of the sound signal

4. Discussion

This study examined whether adding the sound environment would enhance spatial knowledge task performance in a virtual outpatient polyclinic. A significant effect of the experiment group on spatial knowledge acquisition was found in all of the tasks. The audio-visual group had the best performance among the groups in all of the tasks. Another interesting finding of the study was no significant difference between the performance of the only audio group and the visual group. Although the video that the only audio group watched was wiped of all the landmarks such as escalators, admission desks, and elevators, the performance of the participants was comparable to the other groups. In the landmark placement task, the audio-visual group had a significantly higher performance than all the other groups. At the same time, there was no difference between the performance of the only audio group and the visual and control group. Considering that no landmarks were available in this group, it can be concluded that the sound environment is sufficient to provide landmark knowledge. Based on the percentages reported in table 2 and figure 15, it can be seen that the landmarks with sound were remembered better in the only audio and audio-visual group.

In the direction choosing task, the control group had a significantly lower performance than the audio-visual group, but the visual group, only audio and audio-visual group, had a similar performance. In the sorting task, groups 1 and 2 had a significantly lower performance than the audio-visual group. Again, the only audio group had similar performance with the audio-visual group. The audio-visual group had a significantly higher performance. Considering the unavailability of landmarks in the only audio group, the existence of the sound environment has been found sufficient to achieve route knowledge similar to landmark knowledge.

In the sketch-mapping task, similar to the previous tasks, the audio-visual group had a significantly higher performance. There was no significant difference between the performance of the control, visual and only audio groups. In the pointing task, the control group had a significantly lower performance than the other groups. While the visual group had a lower performance than the audio-visual group, there was no difference between the performance of the only audio group and the audio-visual group. Thus, similar to landmark and route knowledge, survey knowledge can also be achieved through the sound environment in the absence of visual cues. This finding indicates that spatial knowledge can be gained without landmarks, which is in line with the findings of Allen (1988). It should also be mentioned that there was no significant difference between the visual and control group except for the pointing task. This shows that visual signage used in isolation does not necessarily enhance performance.

The audio-visual group's significantly higher performance is consistent with the theoretical framework in figure 1 that suggests gathering information from different modalities would lead to a better memory and, therefore, better spatial knowledge. In the audio-visual group, both the phonological loop (sound environment) and visuospatial sketchpad (signage and the surrounding visual environment) are processing information. The dual processing of information may explain the high performance of the audio-visual group in comparison to the other groups. Another speculation is that the sound environment, with its fluctuations across the route, had a better pop-out effect, which is one of the characteristics of good landmarks (Lynch, 1960). The simulated virtual polyclinic is visually uniform with no lighting and color contrast between different route sections, while the sound environment has unique and discernible peaks and dips that may have made the visually uniform spaces distinguishable from each other. However, rather than any environmental sound, the exact sound environment of the traveled route in the outpatient polyclinic with its own unique physical and perceptual characteristics was used. Based on the short-time frequency transform analysis of the signal, it can be seen that the frequency and amplitude of the signal change along the route. Loudness or amplitude, a subjective characteristic of sound, is a perceptual cue for humans and allows them to distinguish different sounds and is related to pressure level and energy distribution in frequency and time (Buus et al., 1997; Jepsen et al., 2008; Secchi et al., 2017). The changes in frequency and amplitude of the signal along the route may have attracted the participants' attention towards the decision points that helped them perform better in spatial knowledge tasks.

Stimulation of the auditory cortex leads to increased activation in the visual cortex (Tranel et al., 2003). The addition of the sound environment may have enhanced activation of the visual cortex leading to a better performance in the audio-visual group. Furthermore, as the radar graph in figure 12 indicates, the sound environment was perceived as chaotic and annoying, associated with arousal. Based on the findings of Thompson et al. (2001), a sound stimulus that is moderately arousing can enhance spatial abilities. The arousing nature of the sound environment may be another reason why the sound environment led to a higher spatial knowledge performance. It should also be mentioned that although the sound environment is perceived negatively, the participants have assessed it as appropriate because appropriate differs from desired (Acun & Yilmazer, 2018, 2019; Axelsson, 2015; Orhan & Yilmazer, 2021).

Audio and visual information in the built environment interact and affect one another (Jeon & Jo, 2020). Audio stimuli that correspond with visual stimuli have a leading effect on visual attention (Liu et al., 2020). In our study, the availability of certain sounds in the sound environment that correspond with a visual element may have attracted the participants' attention, leading to higher performance in spatial knowledge tasks. An example of this audio-visual interaction can be seen in the elevators. The elevator is seen and the sound of its doors opening and closing is heard, in addition to floor announcements and beeping in the background.

Furthermore, considering the use of sound in isolation, a significantly better performance of the audio-visual group can be seen, while in most tasks, there was no significant difference between the visual and only audio group and only audio and audio-visual group. While the combination of visual and audio cues has led to better performance, there is no difference between the performance of the visual and the only audio group. Thus, the sound alone does not lead to a better performance than visual signage, which is in line with the findings of Liu et al. (2020). In their study in railway stations, Liu et al. (2020) conclude that audio-visual interactions and the leading effect of sounds on visual elements can be used in the process of wayfinding system design. An active wayfinding task was not conducted, but good spatial knowledge leads to good wayfinding performance. The findings are also consistent with those of Werkhoven et al. (2014). They compared the effect of visual, auditory, and audio-visual landmarks on spatial memory and navigation in a virtual maze and found better performance in maze drawing, adjacency, and wayfinding tasks for the audio-visual group. Another study with comparable results to ours was conducted by Hamburger and Röser (2014). They compared wayfinding performance for verbal, visual, and acoustic landmarks (animal sounds) in a virtual environment. In their study, acoustic landmarks resulted in good recognition and performance.

In contrast to our findings, Chandrasekera et al. (2015) found no significant effect of soundscape on wayfinding in a virtual maze. The first experiment group int their study had only soundscape landmarks, the second group had only visual landmarks and the third had both visual and soundscape landmarks. The effect of soundscape was significant on immersion however it did not have any significant effect on wayfinding. The reasons behind the contrasting findings can be that in this study the sound environment of the outpatient polyclinic was used as a whole, while they used a church, a market place and a school as visual and soundscape landmarks. Another difference is that while in this study different tasks to measure aspects of spatial knowledge were used, they only used mean time to reach the goal as a measure for wayfinding performance.

Another interesting finding of the study is that there was no significant difference between the performance of the visual group and the control group in all of the tasks except for the pointing task. This may be explained by Arthur and Passini (1992) 's work that states adding signage to facilitate wayfinding does not overcome architectural failures because the ability to read the space is more critical than in situ sign system and signage (Carpman & Grant, 1995; Erkan, 2018). Rousek and Hallbeck (2011) and Lee et al. (2014) indicate that even well-designed signs do not provide enough information to ease wayfinding. Some studies suggest that users ignore graphical expressions and sign objects during wayfinding (Dogu & Erkip, 2000) because the visual system is already occupied with the route's information (Hamburger & Röser, 2014). In the pointing task, individual factors, visuospatial working memory, and rotation abilities affect task performance (Meneghetti et al., 2018). This may explain the significant difference between the groups in this task. More research needs to be done about the other factors that may have caused this significant difference.

Overall, the study confirms the existence of a difference between spatial knowledge acquisition among different experiment groups. The audio-visual group's high performance demonstrates the beneficial effect of sound environment on spatial knowledge acquisition. One limitation of the study is that it cannot be determined whether adding any type of sound would lead to similar results. Other routes and other complex interior spaces such as airports and shopping malls need to be investigated to see if similar results would be achieved. Other limitations of our study are having a non-immersive virtual environment and tasks that are solely based on passive exploration. Although passive exploration has yielded similar results to active exploration studies, adding a task based on active exploration may have enriched our study. Despite these limitations, our study contributes to the available research on spatial knowledge in hospitals.

4. Conclusions

A developed spatial knowledge leads to improved wayfinding performance. Thus, it is essential to investigate alternative and cost-efficient factors other than visual stimuli that affect spatial knowledge acquisition. Modalities apart from vision are suitable for developing mental spatial images that lead to successful navigation. Visual information can be ignored simply by looking in another direction; however, this is not the case for audio information. Thus, it is easier to use sound as a resource for spatial knowledge acquisition. This is important for the aging population and patients with visual disabilities who rely on hearing for spatial information. As mentioned earlier, the participants in the audio-visual group had a significantly higher performance than the other groups; furthermore, the group with only audio had similar or better performance than the visual group. This indicates that even without visual landmarks, the sound environment can compensate and provide sufficient cues for acquiring spatial knowledge. The landmarks that were placed correctly on the sketch map were generally the ones with a unique sound. This finding can be used to create soundmarks that aid spatial knowledge and thus wayfinding. Considering navigation issues associated with visual elements such as signage and the positive effect of adding the sound environment in spatial knowledge tasks, more studies should consider the role certain sound sources can play as soundmarks. Hospitals are generally associated with high sound levels due to reflections from hard surfaces and noise from equipment and people with little consideration on designing the sound environment. The sound environment of the outpatient polyclinic in this study was perceived negatively; however, its addition to the virtual environment aided spatial knowledge acquisition. Thus, even adverse components of the sound environment can be used positively. From a design perspective, our study is a stepping stone for future studies that would focus on sound characteristics such as loudness, pitch, and affective qualities on the formation of soundmarks that can be employed at crossroads, transition spaces, or joint points to aid spatial knowledge acquisition.

Based on the results following conclusion can be drawn.

1. A combination of visual signage and sound environment resulted in higher performance across landmark, route, and survey tasks.
2. No significant difference was found between the performance of the visual group and the control group that shows that signage alone cannot aid spatial knowledge in virtual outpatient polyclinics.

3. The sound environment would be an efficient tool in enhancing spatial knowledge in virtual outpatient polyclinics.
4. The landmarks associated with a sound can compensate for the lack of visual landmarks that can help design a wayfinding system for users with visual disabilities.

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