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Soundspace VR: spatial navigation using sound in virtual reality

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Abstract
Prior research reveals that spatial navigation skills rely mostly in visual sensory abilities, but the study of how spatial processing operates in the absence of visual information is still incomplete. Therefore, a spatial navigation task in virtual reality using auditory cues was developed to study navigational strategies in blindfolded sighted individuals. Twenty healthy adult participants were recruited. The task consisted of a VR scene, in which participants were asked to localize a sound source and move to the target without visual information throughout the entire task. Task difficulty was manipulated by route length and complexity in three different difficulty levels repeated in two different trials. The first trial (learning) consisted of moving to the sound source and then returning to the starting point. The second trial (retrieval) consisted of the same task without the sound source but with auditory cues from obstacles to test spatial learning. Performance was assessed from behavioral measures of execution time, obstacle collisions, and prompts during the task execution. These variables were compared to established neuropsychological instruments for global cognition (Montreal Cognitive Assessment) and memory abilities (Wechsler Memory Scale-R). The results suggested that difficulty level affected navigation performance in both trials. Navigation performance was better in the retrieval trial, but both learning and retrieval trials were explained by global cognitive functioning. These data suggested the Soundspace VR as being effective to study spatial navigation in the absence of visual information and highlight the importance of auditory information from spatial sound cues for spatial navigation and spatial learning.

Keywords Virtual reality · Spatial memory · Spatial navigation · Sound cues

1 Introduction

Spatial navigation is one important function in daily life. Spatial navigation skills are dependent of brain development that is an important asset for animal survival through support of complex foraging behaviors (Haun et al. 2006). Spatial navigation comprises a set of complex skills that involve cognitive functions as memory, visual and spatial perception, and executive functions (Koenig et al. 2011).

Spatial navigation of known places is based in spatial representations created from spatial memory that are used for instance to return to rewarding locations (home, hunting grounds, etc.), present in a wide range of animals: goldfish (e.g., Vargas and Lopez 2005), rodents (e.g., Morris et al. 1986), dogs (e.g., Dumas 1998), and humans (e.g., Allen 1999).

Spatial memory needs constant updating as some spatial features of the environment change rapidly, requiring updated information from the location of objects for guiding mobility (Haun et al. 2006). The functional neuroanatomy of spatial memory includes various structures in the brain, where both hippocampal and parahipocampal regions assume critical roles in encoding and retrieval of spatial information (Schinazi et al. 2016). The hippocampus is thus involved in tasks that depend on relating or combining information from different sources for creating cognitive maps about the environment allowing individuals to plan shortcuts or novel routes for known environments (Eichenbaum 2017).

In the study of spatial navigation, there is a trade-off between the naturalness of the environment with experimental control in such experiments (Dolins et al. 2014). The

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advent of virtual reality makes possible to replicate everyday living situations to study spatial navigation and spatial learning. These features are related to ecological validity which has been described as the degree to which the test reflects a natural and contextually "real" environment (Parsons 2015). Two major points contribute to ecological validity: verisimilitude which describes the similarity between the assessment in the test and a real-life situation; and veridicality which describes precision of what is being assessed compared to daily living (Lages and Bowman 2018). In fact, some studies point to a relationship between navigation performance in real and virtual environments (Cushman et al. 2008).

Moving from point A to B depends on the ability to form, store, and use the cognitive representation of the environment (Allison et al. 2016). For that, two different forms of spatial navigation are defined: (1) local navigation and (2) wayfinding, which differ according to the location of the navigation goal, respectively, in the perceived environment vs. beyond the perceived environment (Franz and Mallot 2000). These forms of spatial navigation represent different navigational strategies, where local navigation is supported by search strategies involving locomotion and goal recognition that do not require prior spatial information about the environment, whereas wayfinding strategy focused on goals beyond the local environment is based in local cues associated with the goal (Eichenbaum 2017). In a more complex form, wayfinding allows to create additional routes and shortcuts to a given goal, which depends on the ability to aggregate all spatial information within a common reference (Eichenbaum 2017).

A further distinction in spatial navigation can be made between locomotion and wayfinding by addressing the aspects of mobility in the former and orientation in the latter. These two forms of spatial navigation are based in allocentric reference frames, in which objects in the surrounding environment are represented relative to the environment, and egocentric reference frames, in which objects are represented relative to the individual (Montana et al. 2019). Therefore, local navigation or locomotion drives from immediate responses to environmental contingencies, relying mostly on egocentric reference frames as acquired spatial information is related to the observer's body. On the other hand, wayfinding involves both allocentric and egocentric reference frames involving more demanding cognitive operations, as decision making about local or remote environments, being also supported in spatial memory representations (Schinazi et al. 2016). It is thought that this type of memory relies mostly on visual information in terms of visual reference points, distances, and directions (Healy and Jozet-Alves 2010).

Several studies aimed to describe the processing of spatial information in blind people, exploring both the formation of spatial representations and mental imagery. According to the Cumulative Model (for more detailed information, see Schinazi et al. 2016), the formation of spatial representations and acquisition of spatial knowledge may be slower for blind people in the absence of visual information, which may explain why an increase in task complexity produce greater impacts in spatial navigation performance of blind compared to sighted people (Cleaves and Royal 1979). However, according to Leo and colleagues (2018), these results are not consistent in explaining the differences in spatial cognitive skills, mainly due to the variability on the degree of visual impairment and to the different methods used to study spatial skills (i.e., mental rotation, egocentric and allocentric representations, etc.). Likewise, there may be also differences in spatial skills between congenitally blind comparing to late-blind individuals. At the level of mental imagery, congenitally blind people have no reference images for mental imagery, but prior neuroimaging studies have suggested that association areas of the visual cortex are larger in blind compared to sighted individuals (Yang et al. 2014). Other studies reveal more activity in the visual cortex in congenitally blind individuals compared to late-blind individuals, possibly reflecting a more demanding condition for visual areas in the absence of a visual representation of the environment in congenitally blind individuals. On the other hand, late-blind individuals may reveal a lower degree of neuroplasticity in visual areas of the brain, leading to difficulties in learning other alternative methods of locomotion (Burton 2003). These findings suggest a different role of the visual cortex between blind and sighted individuals (Schinazi et al. 2016).

In a previous study of Massiceti et al. (2018), the authors sought to investigate spatial navigation by using two different methods of locomotion in a virtual environment in blindfolded sighted participants. The methods used a 3D scene in order to encode visual scenes using spatial audio through simulated echolocation and distance-dependent hum volume modulation—sound produced by the objects modulated by the distance to the object. Participants were asked to navigate in the environment to randomized end points, using each of the developed visual-to-audio mappings (sonification conditions) or using visual information (visual-only baseline condition). Two types of VR environments were constructed: a maze and an obstacle corridor (Massiceti et al. 2018). The main outcomes were based in task completion time and number of collisions. The participants were slower in the audio task compared to the visual baseline, but an improvement in performance was observed throughout learning trials for both conditions. Additionally, the hum volume modulation condition revealed faster navigation times than the echolocation in both scenarios, indicating that learning ability was intact in the absence of visual information.

Another study described a proof-of-concept spatial navigation environment specifically designed for blind people using the sense of depth in VR with sonification (Spillers 2017). Our study followed some of the premises of this environment to conduct a study to understand how spatial processing operates in the absence of vision. Therefore, our study aimed at developing an ecologically oriented VR environment to explore spatial navigation and spatial learning using auditory cues without visual information. We implemented a spatial navigation task in a study-test procedure comprising an initial trial (learning) with auditory target cues as reference points for spatial navigation, along with a further trial (retrieval) without auditory target cues. Our intent was to create a VR task to study spatial learning while manipulating different navigational strategies, local navigation in the first trial where the auditory target cues are accessible in the local environment, and a following trial where the auditory target cues are absent, requiring spatial learning of the environment through wayfinding to reach the target destination. One innovative aspect of this study is related to the ecological validity of the VR setting, which allowed to simulate navigation in the real environment by using the head tracking from the VR device. We measured performance in this task through execution time, number of obstacle collisions and cues during execution on three difficulty conditions according to route length and complexity, being expected that an increase in difficulty would affect navigational performance. We explored whether performance improved with spatial navigation. Furthermore, it was expected that cognitive functioning explains navigation performance considering the underlying cognitive functions supporting spatial navigation.

2 Method

2.1 Participants

The sample for this study consisted of 20 adult participants, recruited from the general community according to a snowball sampling method, where recruited participants contacted other participants to participate in this study. This non-probability sampling technique was chosen in order to reach a community sample of adults. This total sample comprised 14 male participants and 6 female participants (not gender balanced), aged between 20 and 33 years old, with an average age of 26 years (SD = 4 years). Most participants had Secondary (High) schooling level corresponding to ISCED 3 (International Standard Classification of Education). Regarding VR experience, most participants (n = 12) reported intermediate level of experience. These participants were from Lisbon urban region of Portugal, being of Portuguese nationality. The inclusion criteria to participate in this study were being adult with age up to 65 years, with normal or corrected-to-normal vision and hearing, and without history of neurological or psychiatric illness.

2.2 Measures

The assessment of the variables for this study was based on established neuropsychological measures, which are described as performance measures in psychometry requiring different cognitive skills to accomplish the test. The outcomes were based also in an observation grid that was specifically developed for the purpose of this study. The neuropsychological measures consisted of a global measure of cognitive function assessing different cognitive abilities and a measure for memory assessment.

Global cognitive function was assessed using the Montreal Cognitive Assessment—MoCA (original version: Nasreddine et al. 2005; Portuguese version: Freitas et al. 2011) that evaluates different cognitive domains: executive functioning, visual-spatial ability, memory, attention, concentration and working memory, language, temporal and spatial orientation. The test is scored between 0 and 30 points, where the higher scores reflect better cognitive performance. This test is used mainly as a screening tool. According to Freitas et al (2011), the Cronbach's alpha in a Portuguese community sample was equal to 0.775.

Memory was assessed with the Wechsler Memory Scale—WMS-R (original version: Wechsler 1987) that allows a brief assessment memory ability, comprising tests for visual and verbal memory, mental control, logical memory and digit span. This test is scored in a General Memory Index which results from the individual subtests, in which higher scores reflect better memory skills.

Task performance was evaluated with an observation grid developed for this study. The following items were created to assess behavior during spatial navigation in virtual reality: (1) execution time measured in seconds; (2) number of collisions with objects; and (3) number of prompts (verbal instructions during the task).

2.3 Soundspace VR

The Soundspace VR describes a VR task using 3D sound for spatial navigation, developed with VR head mounted display (Oculus Rift S) and using Unity 3D (Unity Technologies®) game engine that allows to create 3D virtual worlds. Previous studies had determined Oculus Rift S accuracy and precision for clinical settings (Jost et al. 2021; Lubetzky et al. 2019); thus, Oculus tracking system allows to track the global position of a VR participant, simultaneous in both VR

Fig. 1 Example of the experimental setting

and real environments, avoiding complex or more intrusive techniques such as motion capture equipment.

The auditory cues were developed and calibrated within the virtual environment using sound software FMOD® for creating realistic a 3D sound environment. After development of the outlines for this task, different scenarios (levels) were created to be used in a limited space of 4 × 4 m, within a university studio lab of 70 m^2 (Fig. 1). The VR environment was calibrated in each capture session to sync the digital space with the studio facilities, enabling the navigation in that real environment with accurate response to the auditory feedback from the Soundspace VR.

This task involved three different levels that differ in route length and complexity to reach the target location. In the Soundspace VR, the difficulty levels were manipulated by route length and complexity. The objects and walls in the digital environment emitted different sounds according to the global position of the participant on the set.

The first level consists of a scenario describing a crosswalk, where the individual is asked to pass only when he/she starts to listen the acoustic sound of the traffic signal (Fig. 2). This was a constant pinging sound at a sound frequency of 1100 Hz from an object further ahead. This sound is better described as a pedestrian crossing walk signal alert. Additionally, the instructions indicate that they have also to cross when it is safe because there is a virtual car passing the road each 30 s, only then they can go ahead and cross. The car itself produces a loud sound indicative of a car motor, indicating that it is in fact passing through. After arriving at the sound location, the individual is asked to return to the initial location by using the same route.

The second level consisted of an obstacle course where the participants were asked to move to the sound source by crossing the obstacles during this route, after which they were instructed to return to the starting point (Fig. 3). There were different routes that could be chosen by the

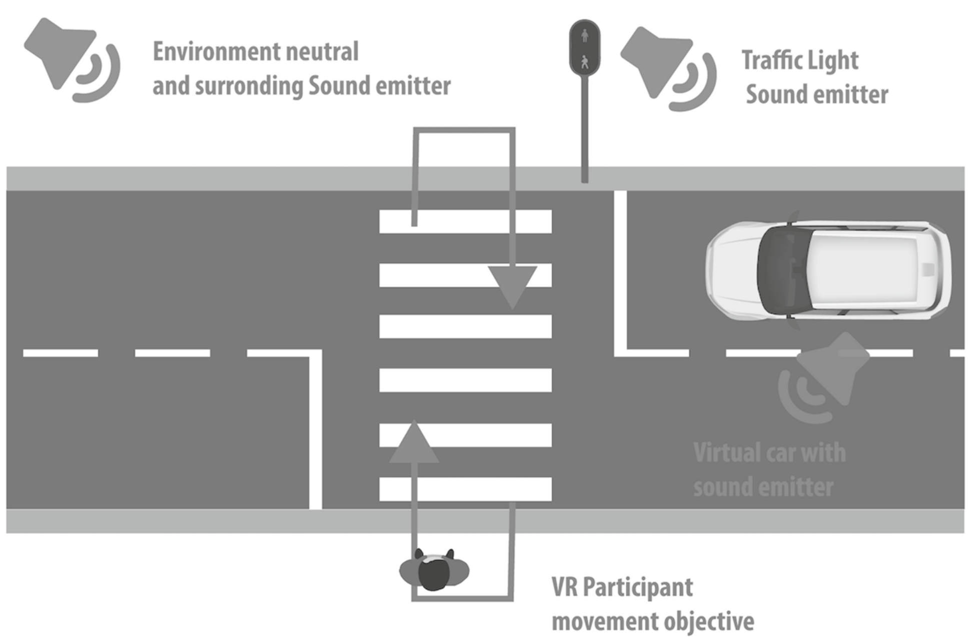


Fig. 2 Crosswalk (level 1) of the Soundspace VR task

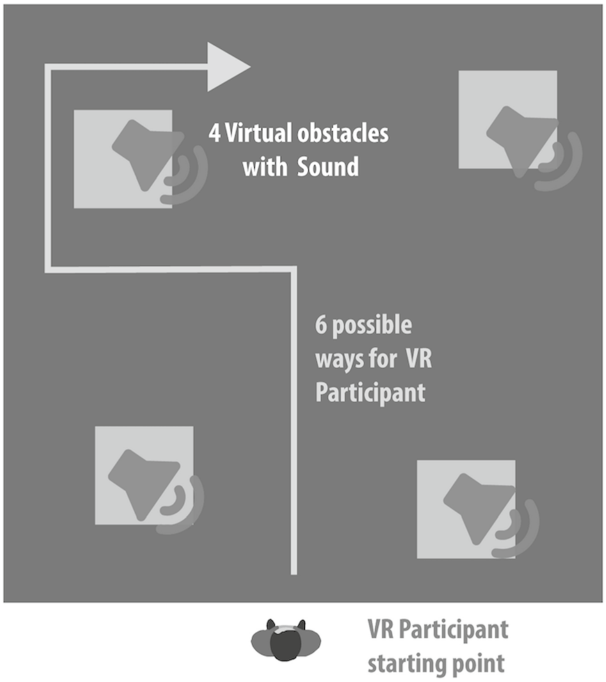


Fig. 3 Obstacle course (level 2) of the Soundspace VR task

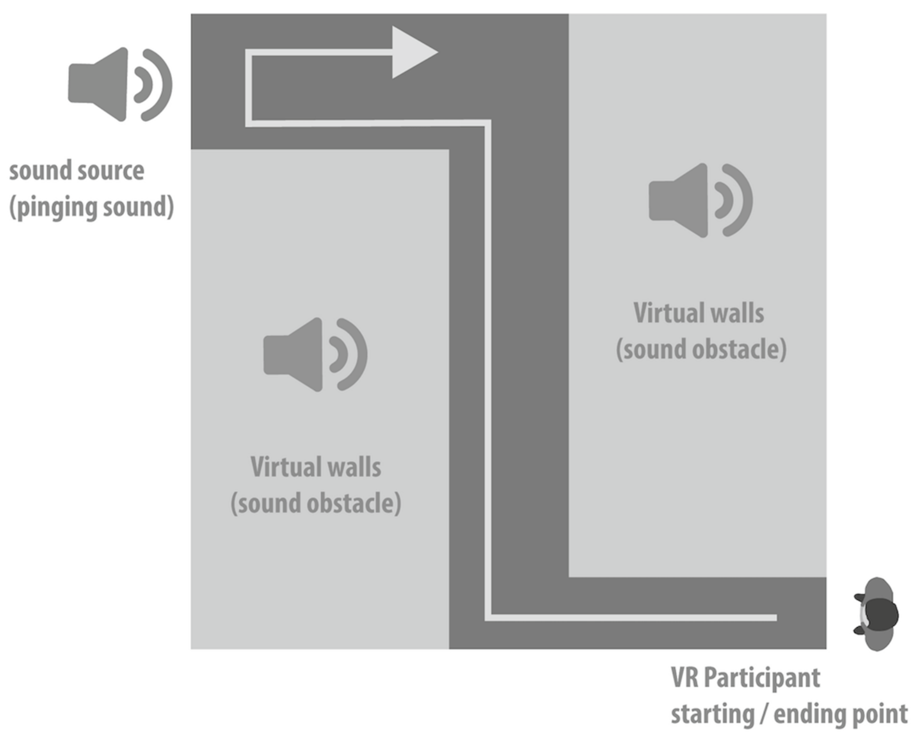
participants. The obstacles produced a high-pitched sound to inform the individual to deviate and continue on the path to the sound target that consisted of a metal pinging sound.

The third level consisted of a maze with two turns where the participants were asked to move to the sound source (metal pinging sound) avoiding collisions with objects and walls of the maze (Fig. 4). After reaching the target, the participants had to return to the starting point.

2.4 Procedure

This project was approved by an ethics committee for the purpose of a study on the research topic related to spatial navigation. The first stage of this study was the development of the Soundspace VR that involved VR development and calibration. After the developmental stage of this study, a sample of adult participants were recruited. After reading and agreeing with the informed consent, the participants filled a brief form for sociodemographic data and they were assessed with neuropsychological instruments for global cognitive functioning (MoCA) and memory abilities (WMS-R). The participants were then exposed to the experimental task. The participants were randomly assigned to different sequence conditions resulting from different combinations for the three levels. At the beginning of each level, the instructions were explained to the participants, along with the meaning of each sound played in these environments. The participants were instructed to move to the sound source avoiding collisions with the objects and the limits of the environment. The sound volume was modulated by the distance to the object producing the sound, being provided to participants through headphones from the VR headset, to best isolate the sound of objects and obstacles.

Fig. 4 Maze (level 3) of the Soundspace VR task



Navigation was performed by walking in the real environment that was calibrated with the Soundspace VR for a 4 × 4 meter area. This task was conducted in MovLab, a motion Capture Lab from University Lusófona.

The test was divided in two different trials. Firstly, this task was centered in local navigation strategies since the auditory target cues were located in the perceived environment, which required participant locomotion to seek for the target sound. After performing a distraction task that consisted of completing the WMS-R subtest related to general information for semantic memory (that took about 5 min), the participants were exposed to the same conditions but without the auditory target cues. The participants were asked to move to the target location without the sound target but with the auditory cues from objects that were played in object proximity so that representation of the environment would be crucial to effectively accomplish the task. After reaching the target, they were asked to return to the starting point as in the first trial. At this stage, navigation required orientation in a form of wayfinding relying in spatial representation of a known environment using the environment cues to reach the target destination.

To ensure the safety of the participants, this experiment was done indoors in an open space without any object that could pose risks to the participants. Moreover, the experimenter was accompanying individuals throughout this experiment. The equipment for this experiment consisted of Oculus Rift S connected to MSI Laptop computer (GL65 gaming series). This experiment took about 30 min to complete.

2.5 Experiment design

This study was based in a within-subjects design with an experiment with two different trials, one for the initial exposure to the spatial navigation task (learning trial) and another for the second exposure without auditory cues (retrieval trial). In each trial the subject had to find the target sound and then return to the starting point, in the first trial using the sound source as a reference point and the second trial without the sound reference, according to three difficulty levels.

The second trial was very similar but without the auditory cues, where the participants were asked to move to the sound target and then return to the starting point only with the sound feedback from the walls of the maze. The sound from objects and walls was modulated according to the proximity from the object. Performance in this task was evaluated by the dependent variables, namely: (1) execution time, (2) number of collisions, and (3) number of prompts.

Table 1 Performance through execution time (seconds) for each condition

Conditions	Minimum	Maximum	Mean	Std. Deviation
ET_T1_L1	18	61	35.30	12.07
ET_T1_L2	24	342	77.15	76.49
ET_T1_L3	21	401	93.95	89.13
ET_T2_L1	17	35	25.65	6.42
ET_T2_L2	18	191	38.80	37.07
ET_T2_L3	19	141	44.40	30.18

Note: *ET* execution time, *T* trial, *L* level of difficulty

Table 2 Performance through number of collisions for each condition

Conditions	Minimum	Maximum	Mean	Std. Deviation
NC_T1_L1	0	4	0.60	1.31
NC_T1_L2	0	6	0.90	1.80
NC_T1_L3	0	4	0.65	1.22
NC_T2_L1	0	3	0.20	0.70
NC_T2_L2	0	2	0.15	0.49
NC_T2_L3	0	3	0.35	0.93

Note: *NC* number of collisions, *T* trial, *L* level of difficulty

2.6 Statistical analyses

Descriptive statistics (mean scores and standard deviations) for the dependent variables according to each condition are presented in Tables 1 and 2, respectively, for execution time and number of collisions. Prompts were not analyzed because the limited number of aids provided to participants that revealed a floor effect. The data was tested for normality for each dependent variable with Kolmogorov–Smirnov test. Given the small sample size and because most of the data revealed non-normal distributions, nonparametric statistics were conducted for testing the study's objectives. The comparison between the three levels of task difficulty was conducted with Friedman test for related samples separately for the learning and the retrieval trial. Friedman test is reported as Chi-square statistic for the mean ranks of related samples. Pairwise comparisons in the Friedman test were corrected with Bonferroni method (alpha/m) in order to avoid incrementing Type I error in these multiple comparisons. The comparisons between performance in the learning trial vs. retrieval trial was done separately for each difficulty level with Wilcoxon Sign Ranks test for two related samples. Finally, the relationship between performance in the Soundspace VR with neuropsychological functioning was tested for groups created from the cutoffs of neuropsychological measures. These differences were analyzed using Mann–Whitney tests. The alpha level was set at 0.05.

3 Results

3.1 Differences in navigation performance between task difficulty levels

The analysis on execution time (seconds) by difficulty level was done with Friedman test for three related samples. This analysis was done for global task performance in each task (level 1, level 2 and level 3) that included finding the target sound and then returning to the starting point. This analysis was conducted separately for the learning and the retrieval trials. The results showed a statistically significant difference between difficulty level both for the learning (X^2 (2) = 21.333; $p < 0.001$) and the retrieval trials (X^2 (2) = 14.427; $p < 0.001$). The pairwise comparisons (alpha/m = 0.016) for each trial suggested an increase in execution time in the learning trial from level 1 to level 2 ($p = 0.005$) and from level 1 to level 3 ($p < 0.001$), whereas in the retrieval trial this increase was only significant from level 1 to level 3 ($p = 0.001$). The mean execution times are depicted in Fig. 5 for each difficulty condition both for learning and retrieval trials (error bars describe the Standard Error).

The same analysis was conducted with Friedman test for obstacle collisions and number of prompts (verbal instructions during the task) during navigation performance, but these analyses did not reveal a significant difference between difficulty levels in either learning and retrieval trials (all p's > 0.05).

3.2 Differences in navigation performance between learning and retrieval trials

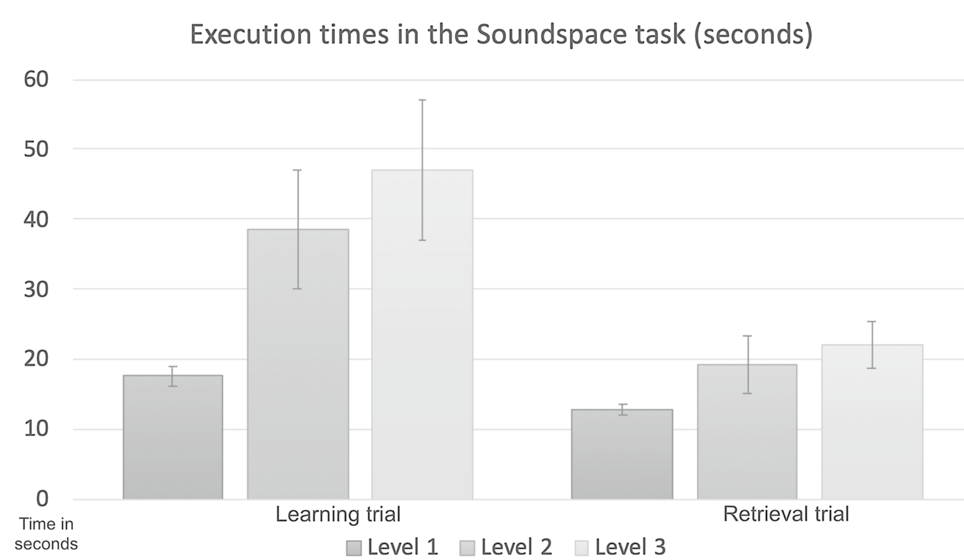
The analysis comparing navigation performance between learning and retrieval trials was conducted separately for each difficulty level with Wilcoxon sign-rank test for each parameter (execution time, obstacle collisions and number of prompts). This analysis on execution time showed statistically significant differences between learning and retrieval trials for level 1 ($Z = -3.060$; $p = 0.002$), level 2 ($Z = -3.156$; $p = 0.002$) and level 3 ($Z = -2.764$; $p = 0.006$). The same analysis on obstacle collisions and number of prompts did not show statistically significant changes between learning and retrieval trials (all p's > 0.05).

3.3 Relationship between navigation performance with neuropsychological functioning

In order to test whether navigation performance in the Soundspace VR is related to neuropsychological functioning, the neuropsychological variables related to the total scores from the MoCA and WMS-R were dichotomized according to the cutoff score. According to Freitas et al. (2011) considering the age cohort of this sample (25–49 years) and education level (ISCED 3), the cutoff for the MoCA is equal to 26 at 1 Standard Deviation below the normative mean. Two groups were created for the MoCA, one group below or equal to the cutoff ($n = 7$) and the other above the cutoff ($n = 13$). As for the WMS-R, there were no published data for Portugal regarding the normative values. Thus, the median point was used as the cutoff score for creating a group below or equal to the median ($n = 12$) and a group above the median ($n = 7$).

The Mann–Whitney test showed statistically significant differences between groups in execution time for level 2

Fig. 5 Execution times in the Soundspace VR task by level and trial



($U = 14.500$; $p = 0.014$) and level 3 ($U = 18.500$; $p = 0.032$) of the learning trial, suggesting that participants with higher scores in the MoCA (i.e., better cognitive functioning) performed these levels of the Soundspace VR faster than participants with lower scores in the MoCA. No differences were found for the WMS-R groups in both learning and retrieval trials (all p's > 0.05).

4 Discussion

This study aimed at developing and evaluating a VR task with auditory cues with different difficulty levels to understand how spatial processing operates in the absence of visual information. For that, three different tasks were used with different navigational demands according to route length and complexity. These different navigation tasks were tested in two trials for exploring how difficulty affects spatial learning: (1) learning phase consisting in local navigation that required participants to move to the auditory target with the aid of auditory cues involving search strategies and locomotion (Franz and Mallot 2000); (2) retrieval phase consisting in wayfinding that required spatial learning of the previous phase by using the spatial representation of the environment to navigate in the absence of the auditory target (Eichenbaum 2017).

The results revealed an improvement in navigation performance from learning to retrieval trials. Performance improved when search and locomotion strategies were replaced by spatial representation of the environment supporting wayfinding strategies. Even in the absence of the auditory target, the use of both allocentric and egocentric cues allowing to use information of the environment and the observer relative to the environment, may have contributed to improve navigation performance.

Furthermore, execution times increased with increasing difficulty both for local navigation (learning) and wayfinding (retrieval). More importantly, these results also show that difficulty in this task affected the spatial navigation performance both for local navigation and wayfinding navigation strategies.

Regarding the relationship between performance in the Soundspace VR with neuropsychological functioning, the data suggested that performance in local navigation task is associated with the level of cognitive functioning. The test used to assess cognitive functioning is a brief cognitive screening test (Nasreddine et al. 2005; Freitas et al. 2011) that evaluates important cognitive domains related to spatial navigation as visuospatial abilities (Koenig et al. 2011). Therefore, this relationship suggests the importance of such skills for navigation in a given space at the level of local navigation. In contrast, wayfinding at the retrieval trial relies more in higher-order cognitive functions related to the prefrontal cortex as executive functions (McCabe et al. 2011) that were not captured by the cognitive screening measure used in our study. The seminal study of Passingham and colleagues (1985) with primates using mazes with food as motivation for performance in a delayed alternation task, showed that damage to the prefrontal cortex may impair spatial navigation skills. Processing and integration of multimodal sensory information depend on executive functions from the prefrontal cortex, which are responsible for goal-directed behavior, behavior regulation, and adapting to new situations of everyday living, while governing social interactions (McCabe et al. 2011). The involvement of the prefrontal cortex was also found in path integration, a key mechanism for spatial navigation for development of cognitive maps that requires basic sensory information, but also higher-order spatial processing, and spatial working memory from the medial prefrontal cortex (Wolbers et al. 2007).

However, the results from our study should be interpreted with caution because several limitations were identified. Firstly, the association between performance in the Soundspace VR with neuropsychological data is limited because the MoCA is a cognitive screening test, which may lack sensitivity in assessing executive functions. Secondly, this analysis was conducted only with bivariate analyses with execution time variable, which distinguished performance in the Soundspace VR, but the size of this sample did not allow to conduct other statistical procedures or to explore these results further at the risk of increasing Type I error. Another important issue relates to the sampling method used in our study that being a non-probabilistic sampling procedure, does not allow to generalize these results in order to draw strong conclusions about these data. According to this design, it was also not possible to dissociate the learning effects of learning from the different navigational strategies due to the previous exposure. It may be also interesting that future studies with the Soundspace VR compare performance between blind and sighted participants to explore whether the increase in task difficulty impacts differently blind and sighted blindfolded individuals (Schinazi et al. 2016). It would be worth studying also whether the pattern of performance is different between sighted and blind individuals for spatial learning of the environment in wayfinding, when performance is not based solely in mobility, but requiring orientation and spatial decision making in using the environmental cues to reach the target destination. Overall, these findings give support to the use of the Soundspace VR task to assess spatial navigation, indicating that this task may be feasible to assess spatial navigation and spatial learning of the environment.

References

Allen GL (1999) Children's control of reference systems in spatial tasks: foundations of spatial cognitive skill? Spat Cogn Comput 1:413–429

Allison SL, Fagan AM, Morris JC, Head D (2016) Spatial navigation in preclinical Alzheimer's disease. J Alzheimer's Dis 52:77–90

Burton H (2003) Visual cortex activity in early and late blind people. J Neurosci 23:4005–4011

Cleaves WT, Royal RW (1979) Spatial memory for configurations by congenitally blind, late blind and sighted adults. J vis Impair Blind 73:13–19

Cushman LA, Stein K, Duffy CJ (2008) Detecting navigational deficits in cognitive aging and Alzheimer disease using virtual reality. Neurology 71:888–895

Dolins FL, Klimowicz C, Kelley J, Menzel CR (2014) Using virtual reality to investigate comparative spatial cognitive abilities in chimpanzees and humans. Am J Primatol 76(5):496–513

Dumas C (1998) Figurative and spatial information and search behavior in dogs (*Canis familiaris*). Behav Proc 42:101–106

Eichenbaum H (2017) The role of the hippocampus in navigation is memory. J Neurophysiol 117(4):1785–1796

Franz MO, Mallot HA (2000) Biomimetic robot navigation. Rob Auton Syst 30:133–153

Freitas S, Simões MR, Alves L, Santana I (2011) Montreal cognitive assessment (MoCA): normative study for the Portuguese population. J Clin Exp Neuropsychol 33:989–996

Haun DBM, Call J, Janzen G, Levinson SC (2006) Evolutionary psychology of spatial representations in the Hominidae. Curr Biol 16(17):1736–1740

Healy SD, Jozet-Alves C (2010) Spatial memory. In: Breed MD, Moore J (eds) Encyclopedia of animal behavior. Academic Press, pp 304–307

Jost TA, Nelson B, Rylander J (2021) Quantitative analysis of the Oculus Rift S in controlled movement. Disabil Rehabil Assist Technol 16(6):632–636

Koenig ST, Crucian GP, Dalrymple-Alford JC, Dünser A (2011) Assessing navigation in real and virtual environments: a validation study. Int J Disabil Hum Dev 10(4):325–330

Lages WS, Bowman DA (2018) Move the object or move myself? Walking vs. manipulation for the examination of 3D scientific data. Front ICT 5:15

Leo F, Tinti C, Chiesa S, Cavaglià R, Schmidt S, Cocchi E, Brayda L (2018) Improving spatial working memory in blind and sighted youngsters using programmable tactile displays. SAGE Open Med 6:2050312118820028

Lubetzky AV, Wang Z, Krasovsky T (2019) Head mounted displays for capturing head kinematics in postural tasks. J Biomech 86:175–182

Massiceti D, Hicks SL, Rheede JJ (2018) Stereosonic vision: exploring visual-to-auditory sensory substitution mappings in an immersive virtual reality navigation paradigm. PLoS ONE 13(7):e0199389

McCabe DP, Roediger HL, McDaniel MA, Balota DA, Hambrick DZ (2011) The relationship between working memory capacity and executive functioning: evidence for a common executive attention construct. Neuropsychology 24(2):222–243

Montana JI, Tuena C, Serino S, Cipresso P, Riva G (2019) Neurorehabilitation of spatial memory using virtual environments: a systematic review. J Clin Med 8(10):1516

Morris R, Hagan J, Rawlins J (1986) Allocentric spatial learning by hippocampectomised rats: a further test of the '"spatial mapping"' and '"working memory"' theories of hippocampal function. Quart J Exp Psychol Sect B 38:365–395

Nasreddine Z, Phillips NA, Bédirian V, Charbonneau S, Whitehead V, Collin I et al (2005) The Montreal Cognitive Assessment, MoCA: a brief screening tool for Mild Cognitive Impairment. Am Geriatr Soc 53(4):695–699

Parsons TD (2015) Virtual reality for enhanced ecological validity and experimental control in the clinical, affective and social neurosciences. Front Hum Neurosci 9:660

Passingham RE (1985) Memory of monkeys (*Macaca mulatta*) with lesions in prefrontal cortex. Behav Neurosci 99(1):3–21

Schinazi VR, Thrash T, Chebat DR (2016) Spatial navigation by congenitally blind individuals. Wiley Interdiscip Rev 7(1):37–58

Spillers F (2017) Soundspace: toward accessible spatial navigation and collaboration for blind users. 5th ACM Symposium on Spatial User Interaction (SUI), Brighton, England

Vargas JP, Lopez JC (2005) Different ways of encoding geometric information by goldfish (*Carassius auratus*). J Comp Psychol 119:458–460

Wechsler D (1987) WMS-R: Wechsler memory scale-revised. The Psychological Corporation, San Antonio

Wolbers T, Wiener JM, Mallot HA, Buchel C (2007) Differential recruitment of the hippocampus, medial pre-frontal cortex, and the human motion complex during path integration in humans. J Neurosci 27:9408–9416

Yang C, Wu S, Lu W, Bai Y, Gao H (2014) Anatomic differences in early blindness: a deformation-based morphometry MRI study. J Neuroimaging 24(1):68–73