Virtual Reality

Spatial navigation using sound: Data from Soundspace task in virtual reality

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Abstract

Prior research reveal 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 sighted individuals. Twenty healthy adult participants were recruited. The task consisted of a VR scene, in which participants were asked to localize the sound source and move to the target without visual information (i.e. blindfolded). Task difficulty was manipulated by route length. The participants were first exposed in a study phase with the objective to move to the sound source and then return to the starting point. In a test phase, the participants performed the same task without the sound source but with auditory cues from obstacles to test spatial learning. This manipulation allowed to assess navigational strategies as local navigation in the first and wayfinding in the second phase. Performance was assessed from behavioral measures of execution time, obstacle collisions, and prompts during the task execution. These variables were correlated with established neuropsychological instruments for global cognition and memory abilities. The results revealed a relationship between executive functioning and task performance. Global performance was better in wayfinding involving spatial learning, while increases in task difficulty affected performance through execution time only for local navigation. These data reveal the importance of auditory information from spatial sound cues for spatial learning and navigation in a known environment.

Keywords: Virtual Reality; Spatial Memory; Spatial Navigation; Sound.

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, Call, Janzen & Levinson, 2006). Spatial navigation comprises a set of complex skills that involve cognitive functions as memory, visual and spatial perception, and executive functions (Koenig, Crucian, Dalrymple-Alford & Dünser, 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.), being demonstrated in a wide range of animals, from goldfish (e.g., Vargas & Lopez, 2005), rodents (e.g., Morris, Hagan & Rawlins, 1986), to 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. More specifically, parahipocampal regions, including the posterior parahippocampal cortex and the retrosplenial parietal region, known as parahipocampal place area (PPA), were found to be activated when individuals viewed scenes (Epstein & Kanwisher, 1998), compared to objects and faces (Hansson, 2004). Some authors argue that the parahipocampal gyrus is responsible for coding the spatial structure of the environment, while the retrosplenial cortex for placing the scene within the representation of environment. Moreover, clinical evidence of patients with acquired brain injuries in the temporal cortex suggests the involvement of parahipocampal gyrus in topographic orientation while the retrosplenial in spatial navigation (Hartley, Lever, Burgess & O'keefe, 2014).

The hippocampus is involved in tasks that depend on relating or combining information from different sources for creating cognitive maps about the environment (Eichenbaum, 2017). Spatial navigation is based in cognitive maps that allow individuals to plan short-cuts or novel routes for known environments, being associated with hippocampus activity in neuroimaging studies (e.g., Hartley, Maguire, Spiers & Burgess, 2003). Evidence for this relationship comes from a seminal study on the London taxi drivers, which showed a larger volume of right posterior hippocampus that increased according to navigation experience of taxi drivers (Maguire, Woollett & Spiers 2006).

Moving from point A to B depends on the ability to form, store and use the cognitive representation of the environment (Allison, Fagan, Morris & Head, 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. These forms of spatial navigation represent different navigational strategies (Eichenbaum, 2017). Local navigation is supported by search strategies involving locomotion and goal recognition, that do not require prior spatial information about the environment (Eichenbaum, 2017). On the other hand, wayfinding strategy focused on goals beyond the local environment is based in local cues associated with the goal. 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).

Other distinction may be simply between locomotion and wayfinding, addressing the aspects of mobility in the first and orientation in the second. In either classification, such navigational strategies are based in environmental cues (Schinazi, Thrash & Chebat, 2016). These cues support allocentric reference frames of the environment as viewpoint-independent representations, and egocentric reference frames as viewpoint-dependent representations (Montana, Tuena, Serino, Cipresso & Riva, 2019). Therefore, local navigation or locomotion drives 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, which are supported in spatial memory representations (Schinazi et al., 2016). It is thought this type of memory relies mostly in visual information in terms of visual reference points, distances and directions (Healy & Jozet-Alves, 2010).

Several studies aimed to describe processing of spatial information in blind people, exploring both the formation of spatial representations and mental imagery. According to the Cumulative Model (see Schinazi et al., 2016), 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 people comparing to late-blind people. 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, Wu, Lu, Bai & Gao, 2014). Other studies reveal more activity in the visual cortex in blind individuals compared to late-blind people, 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 people 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).

Most research about spatial navigation relies in laboratory studies that may not reflect the demands of real life situations. The advent of virtual reality makes possible to replicate everyday living scenes that may allow to study spatial navigation and memory. 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 (Bohil, Alicea, Biocca, 2011). 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 (Parsons, 2015). Virtual reality may contribute to increase ecological validity, but also to manipulate and control more effectively spatial navigation variables (Lages & Bowman, 2018).

In a previous study of Massiceti, Hicks, & Rheede (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. 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 but suggesting that intact learning abilities even in the absence of visual information.

In order to better understand how spatial processing operates in the absence of visual information, our study aimed at developing a virtual reality environment to explore spatial navigation and spatial learning with auditory cues. We implemented a spatial navigation task in a study-test procedure comprising an initial block (study) with auditory target cues as reference points for spatial navigation, along with a further block (test) without auditory target cues. Our intent was to create a VR task manipulating different navigational strategies, local navigation in the first block where the auditory target cues are accessible in the local environment, and a following block where the auditory target cues are absent, requiring spatial learning of the environment through wayfinding to reach the target destination. The use of the head tracking from the VR setup allowed to simulate navigation in the real environment. We measured performance in this task through execution time, number of obstacle collisions and prompts during execution on three difficulty conditions according to route length, being expected that an increase in difficulty would affect navigational performance. This prediction is aligned with the results from Dolins, Klimowicz, Kelley and Menzel (2014) showing that maze complexity affected spatial navigation efficiency. We explored also whether performance improved in the second block (without auditory target cues) through spatial learning. Furthermore, it was expected that performance in spatial learning block correlated with cognitive functioning domains.

Method

Participants

The sample for this study consisted of 20 adult participants, recruited from the general community according to a snowball sampling method. This total sample comprised 14 male participants and 6 female participants, aged between 20 and 33 years-old, with an average age of 26 years (SD = 4 yrs). Most participants had Secondary schooling level. Regarding virtual reality experience, most participants (n = 12) reported intermediate level of experience/knowledge. 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, without history of neurological or psychiatric illness.

Measures

The assessment of the variables for this study was based on established neuropsychological measures along with an observation grid that was developed specifically for the purpose of this study. The neuropsychological measures consisted of a global cognitive measure and another measure to assess memory abilities.

Global cognitive functioning was assessed using the Montreal Cognitive Assessment - MoCA (original version: Nasreddine, Phillips, Bédirian, et al., 2005;

Portuguese version: Freitas, Simões, Santana, Martins & Nasreddine, 2013) 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 to 30 points, where the higher scores reflect better the cognitive performance.

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; 2) number of collisions with objects; and 3) number of prompts (verbal instructions during the task).

Soundspace task

The Soundspace task describes a virtual reality 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 (Tyler, Bradley, & Jonathan, 2019; Lubetzky, Wang, & Krasovsky, 2019), thus Oculus tracking system allows to track the global position of a VR participant, simultaneous in both VR and real environments, avoiding complex or more intrusive techniques such as motion capture process.

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 4x4 meters, within a university studio lab of 70 meters square. 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 task.

This task involved three different levels that differ in route length to reach the target location. 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 (Figure 1). 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 seconds, only then they can go ahead and cross. After arriving at the sound location, the individual is asked to return to the initial location.

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 (Figure 2). There were different routes that could be chosen by the 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 pinging sound.

The third level consisted of a maze with two turns where the participants were asked to move to the sound source (pinging sound) avoiding collisions with objects and walls of the maze (Figure 3). After reaching the target, the participants had to return to the starting point.

Procedure

This project was approved by an ethics committee for the purpose of an exploratory study on the research topic related to spatial navigation.

The first stage of this study was the development of the Soundspace task, that involved VR development and calibration. After the developmental stage of this study, a sample of adult participants were recruited for this study. 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 study groups were randomly assigned to six sequence conditions resulting from different combinations for the three levels. The participants were asked to move to the sound source avoiding collisions with the objects and the limits of the environment. Navigation was performed by walking in the real environment that was calibrated with the Soundspace task for a 4X4 meter area (Figure 4). This task was conducted in MovLab, a laboratory of movement capture from University Lusófona in Lisbon, Portugal.

This test was divided in two different blocks. In the first place, 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 distracting task that consisted of completing the WMS-R subtest related to general information for semantic memory (that took about 5 minutes), 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 also to return to the starting point as in the first block. 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.

For ensuring security of the participants, this experiment was done indoor 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).

Results

The data was analyzed with Statistical Package for Social Sciences (v.25). This study was based in a within-subjects design with an experiment with two different blocks, one for the initial exposure to the spatial navigation task (study phase) and another for the second exposure without auditory cues (test phase). In each phase the subject had to find the target sound and then return to the starting point (i.e. trial), in the first block using the sound source as a reference point and the second block without the sound reference, according to three difficulty levels (i.e. difficulty).

The second block 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. Performance in this task was evaluated by the dependent variables, namely: 1) execution time, 2) number of collisions and 3) number of prompts. Descriptive statistics for the dependent variables according to each condition are presented in Table 1 and Table 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.

Inference statistics were performed with repeated measures ANOVA for each dependent variable. Two repeated measures ANOVA were conducted according to a 2X2X3 factorial design: block (study vs. test) per trial (locating the target vs. returning to the starting point) per difficulty (level 1 vs. level 2 vs. level 3). The statistical main and interaction effects were explored further using simple effects analysis for bivariate comparisons with Bonferroni correction method. The effects in each comparison were reported as partial Eta-squared effects. The alpha level considered for statistically significant comparisons was .05, corresponding to a 95% confidence level.

The analysis on execution time through this ANOVA revealed significant main effects for block (F(2, 19) = 8.410; Eta^2_p = .307; p < .01) and difficulty (F(1, 19) = 10.683; Eta^2_p = .360; p < .01), suggesting higher execution time for the study block corresponding to local navigation strategy. Bonferroni corrected pairwise comparisons were performed for difficulty, which revealed that increases in execution times were significant only when comparing the easiest with the most difficult level (p < .05). In addition, a significant interaction effect between these factors was also observed (F(2, 38) = 4.074; Eta^2_p = .177; p < .05). Bonferroni corrected simple effect analyses revealed that execution time was higher in the study block for local navigation by difficulty level (all p’s < .05), as shown in Figure 5. Difficulty level did not produce an effect in the test block corresponding to spatial learning supporting wayfinding.

The same analysis was conducted for number of collisions in the spatial navigation task, which revealed only a main effect of trial (F(2, 38) = 4.687; Eta^2_p =

.204; $p < .05$), suggesting a higher average number of errors in the first trial when the participants moved to the sound target comparing with the return to the starting point (M = .375; SE = .107 vs. M = .100; SE = .056).

Finally, product-moment Pearson correlations were conducted to understand whether performance in the Soundspace task was correlated with neuropsychological functioning. We focused only in execution time as this indicator was better at distinguishing performance in the Soundspace. The results indicated that Visuospatial subtest of the MoCA correlated with execution time in the study block for Level 1 ($r = -.561$; $p < .05$), whereas Abstraction subtest correlated with execution time for Level 2 ($r = -.652$; $p < .01$) and for Level 3 ($r = -.635$; $p < .01$), each of these tasks on the trial corresponding to the return to the starting point.

Discussion

This study aimed at developing and evaluating a virtual reality task with auditory cues for spatial navigation to understand how spatial processing operates in the absence of visual information. We created a spatial navigation task manipulating navigational strategies in two different blocks. Navigational strategies in the first block (study) consisted of local navigation that required patients to move to the auditory target with the aid of auditory cues, where navigation in the environment involved mainly search strategies and locomotion (Eichenbaum, 2017). The second block (test) consisted of wayfinding strategies as performance in this block required spatial learning by using the spatial representation of the environment to navigate in the absence of the auditory target. Here, performance was not based only in search and locomotion strategies, instead it may have required orientation relying in spatial representation of the known environment to reach the target destination (Schinazi et al., (2016) Our intent with this design was to create a virtual scenario with different navigational demands to study whether performance is different according to navigational strategy and difficulty. The results revealed an improvement in task performance from study to test blocks. 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, improved task performance.

Furthermore, execution times increased with increasing difficulty only for local navigation (Dolins et al., 2014) but not in wayfinding. No differences were observed for locomotion in the first block with the auditory target or without the auditory target (i.e. returning to the starting point).

Regarding the relationship between performance in the Soundspace task with neuropsychological functioning, the data suggested that performance in local navigation task is associated with visuospatial ability, whereas performance in wayfinding is associated with abstraction ability. Both visuospatial and abstraction are components of executive functioning (Nasreddine et al., 2005). Here visuospatial ability was assessed with a brief version of the Trail Making Test (TMT) and a cube copy test, which involves set-shifting abilities to shift between number and letter information in the TMT and visuospatial perception. In contrast, abstraction was assessed with word similarities (Dubois, Slachevsky, Litvan, & Pillon, 2000). We may speculate abstraction as an higher-order function may play an important role to explain decision making processes in wayfinding, more than set-shifting and visuospatial perception, that may be important abilities to support navigational strategies from locomotion or local navigation. In fact, previous studies found that beyond the hippocampus and the parahippocampal region

(Eichenbaum, 2017), the pre-frontal cortex is also involved in spatial navigation, supporting executive functioning (McCabe, Roediger, McDaniel, Balota & Hambrick, 2011) and spatial decision making (Schinazi et al., 2016). 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 pre-frontal cortex may impair spatial navigation skills. Processing and integration of multimodal sensory information depend on executive functions from the pre-frontal 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 pre-frontal 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 pre-frontal cortex (Wolbers, Wiener, Mallot & Buchel, 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 task with neuropsychological data is limited because the MoCA is a cognitive screening test, which may lack in sensitivity in assessing such executive functions. Secondly, this analysis was conducted only with bivariate correlations with execution time variable, which distinguished performance in the Soundspace task, but the size of this sample did not allow to conduct other statistical procedures or to explore these correlations further at the risk of increasing error.

It may be interesting that future studies with the Soundspace task compare performance between blind and sighted participants to understand whether the increase in task difficulty impact differently blind and sighted blindfolded individuals. According to the Cumulative Model (see Schinazi et al., 2016), an increase in task difficulty may have a greater impact in blind people compared to sighted people. It will worth studying also whether the pattern of performance is similar 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 task to assess spatial navigation, indicating that this task may feasible to assess spatial navigation and spatial learning of the environment.

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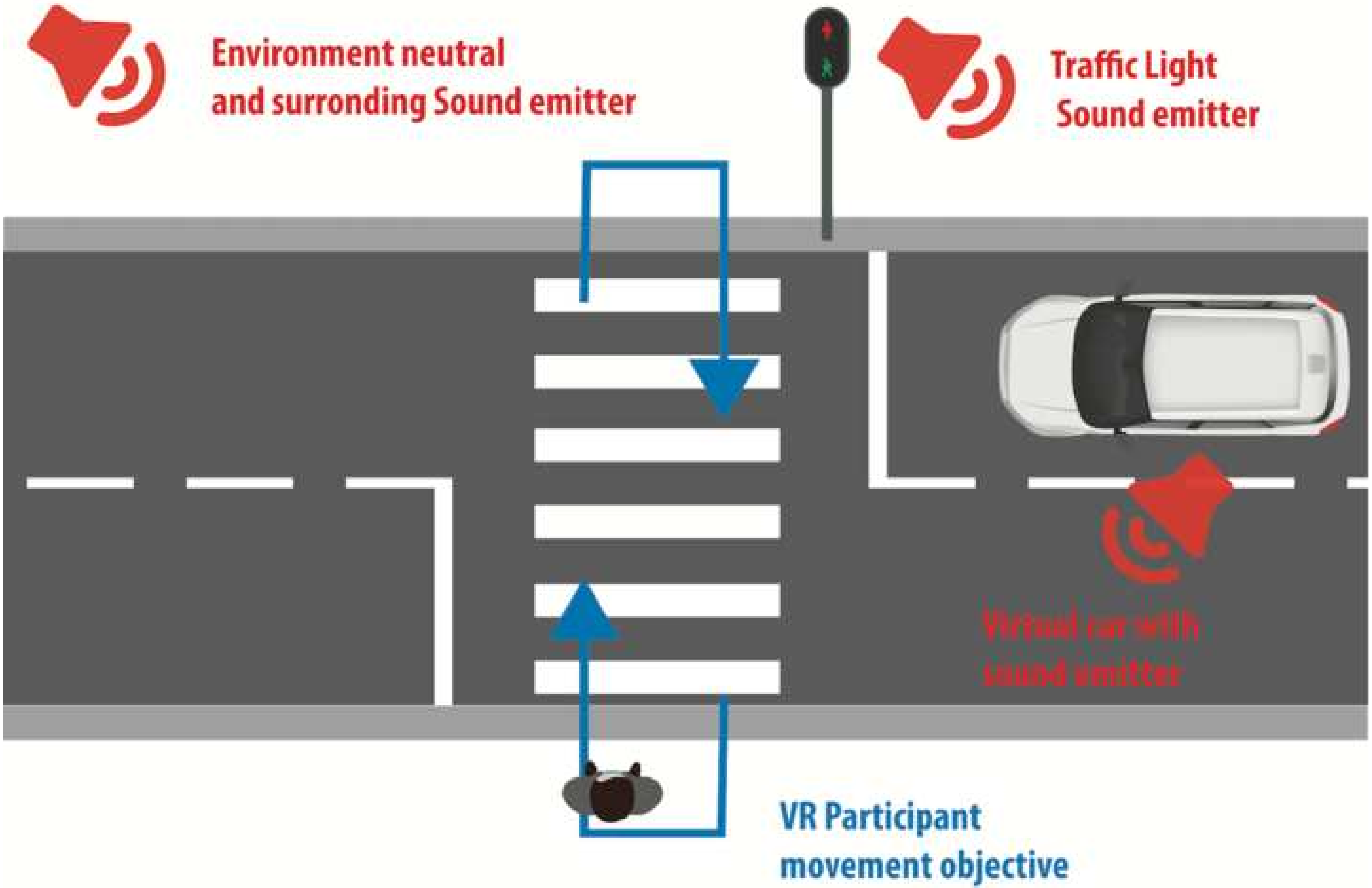
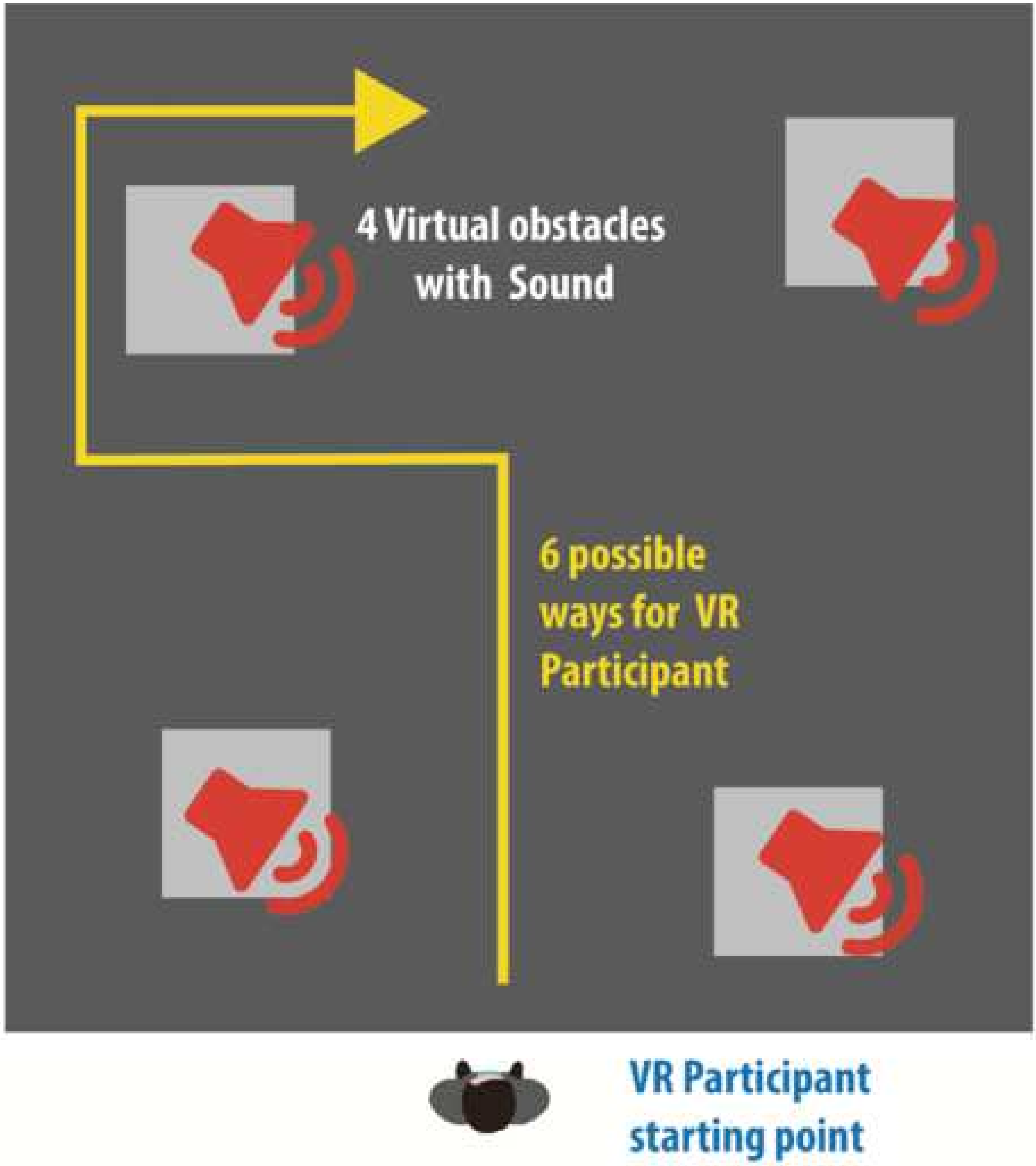
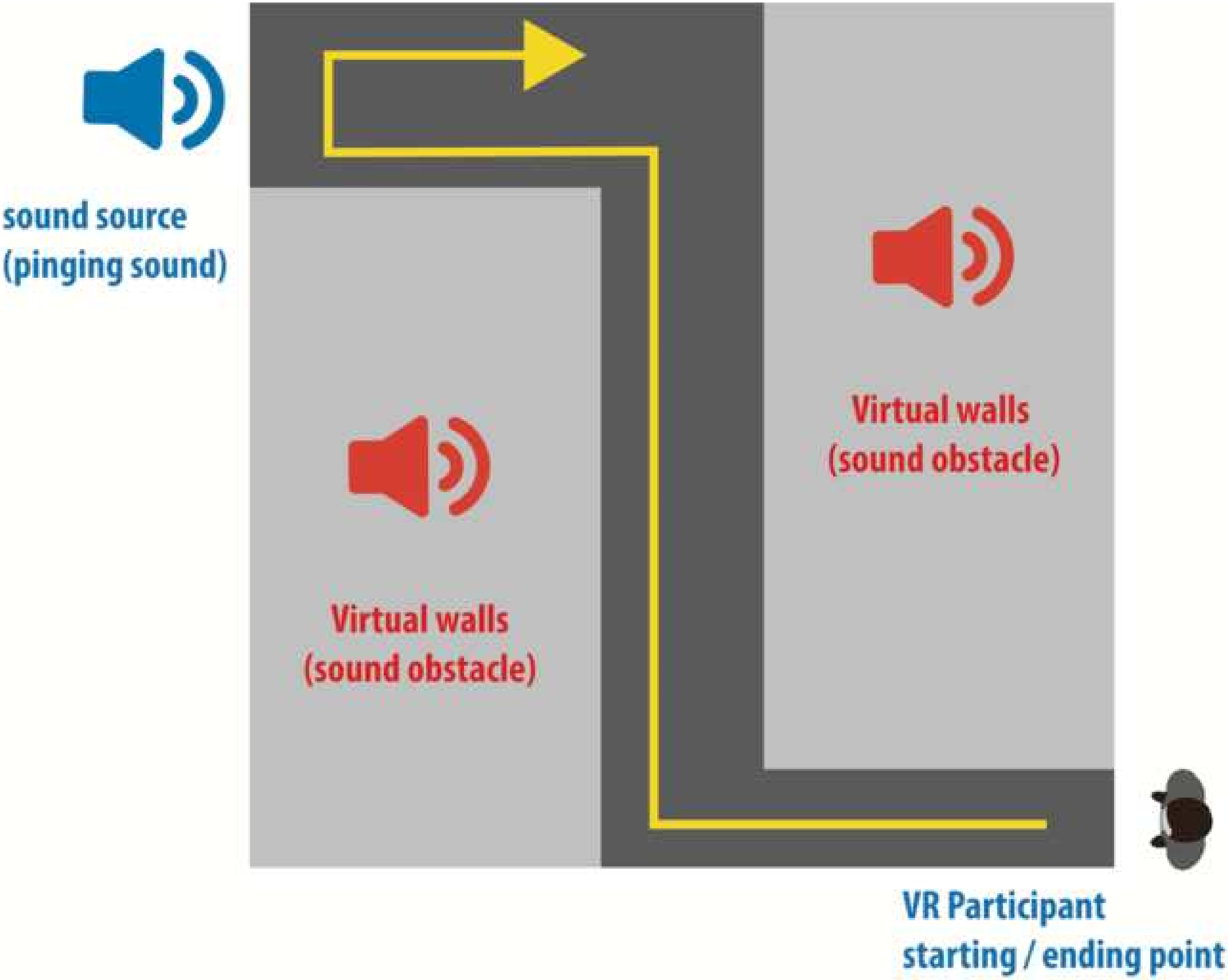
Figure 1


Environment neutral
and surronding Sound emitter
Traffic Light
Sound emitter
Virtual car with
sound emitter
VR Participant
movement objective


4 Virtual obstacles
with Sound
6 possible
ways for VR
Participant
VR Participant
starting point


sound source
(pinging sound)
Virtual walls
(sound obstacle)
Virtual walls
(sound obstacle)
VR Participant
starting / ending point

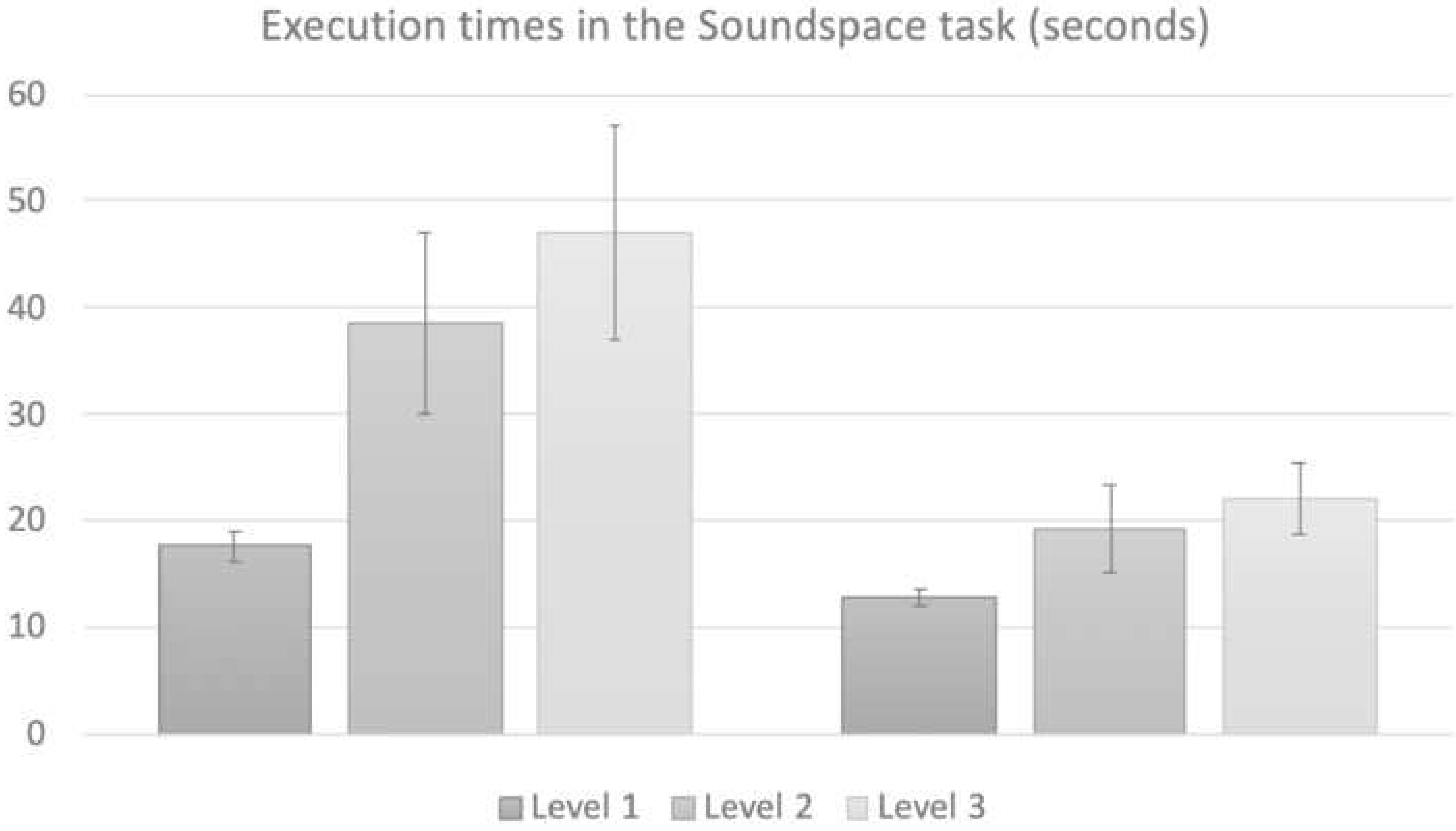

Execution times in the Soundspace task (seconds)
60
50
40
30
20
10
0
Level 1
Level 2
Level 3

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

Conditions	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**
ET_B1_L1_T1	14	34	23.85	6.12
ET_B1_L2_T1	7	121	38.15	28.58
ET_B1_L3_T1	17	145	56.70	43.69
ET_B1_L1_T2	3	40	11.45	8.84
ET_B1_L2_T2	4	304	39.00	70.27
ET_B1_L3_T2	2	301	37.25	68.08
ET_B2_L1_T1	10	30	19.65	5.34
ET_B2_L2_T1	11	56	23.50	10.34
ET_B2_L3_T1	14	134	32.40	26.73
ET_B2_L1_T2	2	20	6.00	4.40
ET_B2_L2_T2	3	135	15.30	28.58
ET_B2_L3_T2	4	36	12.00	9.91

Note: ET – Execution time; B – Block; L – Level of difficulty; T – Trial.

Table 2. Performance through number of collisions for each condition.

Conditions	Minimum	Maximum	Mean	Std. Deviation
ET_B1_L1_T1	0	4	.50	1.28
ET_B1_L2_T1	0	5	.75	1.45
ET_B1_L3_T1	0	4	.55	1.19
ET_B1_L1_T2	0	2	.10	.45
ET_B1_L2_T2	0	3	.15	.67
ET_B1_L3_T2	0	2	.10	.45
ET_B2_L1_T1	0	3	.20	.70
ET_B2_L2_T1	0	1	.05	.22
ET_B2_L3_T1	0	3	.20	.70
ET_B2_L1_T2	0	0	.00	.00
ET_B2_L2_T2	0	2	.10	.45
ET_B2_L3_T2	0	3	.15	.67

Note: ET – Execution time; B – Block; L – Level of difficulty; T – Trial.