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Differences between blind people's cognitive maps after proximity and distant exploration of virtual environments

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A B S T R A C T

Visits to simulations of real spaces in virtual reality have been proposed as a means for blind people to gain spatial knowledge regarding the disposition of obstacles within a place before actually visiting it. Within the present study, different configurations of distant and proximity exploration were compared to each other, in order to test whether differences in effectiveness and efficiency lead to changes in exploration behaviour, without a detrimental impact on cognitive-map quality and usefulness. Evidence supports effectiveness improvements due to distant exploration (p-value = 0.0006). The flat-spotlight distant-configuration entails a 53% reduction in discovery time (p-value = 0.0027). A trend is observed entailing a 38% reduction in the duration of the overall exploration stage for a flat spotlight configuration (p-value = 0.067). Wall-detection effectiveness alters exploration duration (p-value = 0.012). Improvements in effectiveness and discovery time are associated with shorter overall exploration time. Duration of exploration after discovery time depends on wall-detection effectiveness. Benefits from a distant exploration configuration are not enough to build better cognitive maps.

1. Introduction

1.1. Background

1.1.1. Blindness and spatial thought

There have been three traditional hypothesis about whether blind people can understand and manipulate spatial concepts. Andrews (1983) referred to them as deficiency, inefficiency, and difference theories. Deficiency theory argues that congenitally blind people are unable to develop spatial thought because vision experience, and its corresponding perceptual processes, are mandatory requirements. Inefficiency theory suggests that blind people can understand spatial concepts but cannot fully develop their spatial abilities due to their perceptual limitations. Finally, difference theory suggests that blind people are as capable as sighted people of spatial thought; and that difference in performance and behaviour come from a lack of information (Kitchin, Blades, & Golledge, 1997).

Subsequent evidence reinforces inefficiency and difference postulates. Zwiers, Van Opstal & Cruysberg (2001) found no differences between early blind and sighted people when pointing toward the locations of 2D-sound sources. Tinti, Adenzato, Tamietto, and Cornoldi (2006) compared the ability of blind-folded sighted people, congenitally blind people, and late-blinded people to develop spatial inferential complex representations. They found no significant differences between the two latter groups; which outperformed sighted people. Loomis, Klatzky, and Giudice (2013) even discuss the concept of spatial image: a representation of spatial knowledge that can be instantiated in working memory, e.g. during spatial update, independently of input modality (i.e. any of the three spatial senses, language, and long-term memory).

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1.1.2. Acquisition of spatial knowledge

Blind people may gain spatial knowledge of a particular place by physically navigating it and learning the disposition of obstacles as they run into them. We refer to this paradigm as proximity exploration, for people obtain information at the reach of hand or the reach of the cane. Systems aiming to help blind people to find their way, by reporting the presence of obstacles at longer distances, have been proposed. They range from simple ultrasound devices to sophisticated systems based on a combination of GPS, GIS and Web cybercartography (Bartyna et al., 2005; Punwilai, Noji, & Kitamura, 2009; Sanchez, Aguayo, & Hassler, 2007; Wang, Li, & Li, 2012; de Almeida & Tsuji, 2005); solutions also include robotic navigation (Knight, 2012; Kaiser & Lawo, 2012). However, spatial knowledge goes beyond obstacle avoidance; it comprises the development of a priori knowledge regarding spatial layout and self-location within said layout.

Visits to virtual reality simulations of real spaces have been proposed as a means for blind people to gain spatial knowledge regarding the disposition of obstacles, either structures and objects, within a place, before actually visiting it. The usual platform supporting these virtual environments are personal computers, with the exception of Campos, Sánchez, Martins, Santana & Espinoza (2014) which describes an implementation for smartphones. Usually, participants are explicitly instructed to learn the layout modelled by the virtual environment. Lahav and Mioduser (2008b) observed that blind users of such a virtual environment acquired better spatial knowledge than non-users; they also observed that the former performed better in real-world tasks. An alternative approach studies the effect of gamification, i.e. participants play a game that takes place within the virtual model of an actual building, but they are not explicitly instructed to learn the scene layout. Both approaches have shown to be effective, but Merabet, Connors, Halko, and Sánchez (2012) and Connors, Chrastil, Sánchez, and Merabet (2014) observed that gamification provided blind people with a richer set of alternative routes and shortcuts.

Studies base their virtual environments in navigation models that mimic real-world proximity exploration (i.e. information is provided to blind people as an avatar passes close by obstacles while walking along the virtual environment). Picinali, Afonso, Denis, and Katz (2014) observed that passive exploration did not produce good results; spatial knowledge acquisition improved when blind people directly controlled the movements of the avatar. Besides interactivity, multimodality has also been shown to improve spatial knowledge acquisition; Lahav and Mioduser (2004), began by providing force feedback via a haptic device acting as virtual cane; their system was expanded to improve multimodality, with a stress on sound-based feedback (Lahav, Schloerb, & Srinivasan, 2015; Lahav, Schloerb, Kumar, & Srinivasan, 2008; Lahav, Schloerb, Kumar, & Srinivasan, 2012). Different forms of sound-based feedback may be found in literature but they have not been tested against each other. Merabet and Sánchez (2016) use iconic spatialized audio cues to report the functionality of obstacles; Maidenbaum, Buchs, Abboud, Lavi-Rotbain, and Amedi (2016) played different tunes depending on the nature of the obstacle and its relative position to the avatar.

1.1.3. Assessment of spatial knowledge

Internal representations of spatial knowledge are referred to as cognitive maps (Tolman, 1948). As a consequence, the process of acquiring spatial knowledge is also known as cognitive mapping (Kitchin, 2001) The nature of cognitive maps is somehow controversial; while many authors like Kaplan, Tversky, Stea, Blaut, Walmsley or Downs, understand them as an actual mental construct storing spatial information; some others like Siegel think the term represents just a convenient but fictional convention (Kitchin, 1994). Being an internal representation, in order to be able to assess them, they must be externalised. A review of different techniques for the externalization of cognitive maps may be found at Kitchin and Jacobson (1997). It shows a rather high variety of methods that continues to this day.

A common approach to assess cognitive map quality is by directly testing its usefulness to help navigating real spaces; quality is usually modelled as the success or failure in completing some set of particular tasks (Merabet et al., 2012). Another approach involves asking participants to provide a verbal description of the scene; which may be complemented by asking participants to build realistic or schematic models of the scene under exploration. Verbal descriptions are assessed in terms of the percentage of elements correctly identified, and may be complemented with a subjective valuation of relationship descriptions; while modelling kits are used to assess object location estimations (Lahav & Mioduser, 2008a, 2008b; Papadopoulos, Koustriava, & Barouti, 2017; Xie et al., 2017). Finally, there are examples of questionnaires with predefined questions (Giraud, Brock, Macé, & Jouffrais, 2017). These works analyse different externalizations' dimensions in a siloed way, but they do not describe any index able to provide an overall assessment.

1.2. Objectives and hypotheses

Rieser, Guth, and Hill (1982) and Golledge, Klatzky, and Loomis (1996) emphasise that vision is the main source of perceptual updating; so building and maintaining cognitive maps without the continuous flow of information that vision provides is very difficult. In addition, the lack of information regarding distant obstacles and events also hampers blind people's ability to acquire and maintain spatial knowledge. The proximity-exploration approach is sub-optimally adapted to fulfil these requirements. We propose a distant-exploration approach where blind people can explore the room by controlling the direction of the avatar's line of sight. Feedback regarding obstacles beyond the reach of the cane may be obtained with no need of making the avatar to walk along the virtual space. We think that developing location and interaction technologies around this distant-exploration concept will result in blind-friendly environments fostering blind people's independent behaviour and empowering them to abandon passive attitudes. However, distant exploration in virtual environments has been an object of little study so far. We modelled a software entity, known as the spotlight, so that blind people could control the region of the room in which they wanted to focus their attention; allowing them to reach locations even beyond the reach of the cane. Further description of the spotlight may be found in section 2.2.2.

This study focuses on the causes and consequences of difference in exploration behaviour when blind people explore a virtual environment by means of a distant approach compared to a proximity approach. We hypothesise that distant exploration improves efficacy (i.e. a higher percentage of obstacles is detected during an exploration session) and efficiency of the exploration process (i.e. blind people need less time to detect obstacles for the first time); in addition, we hypothesise that those changes have an impact on blind people's exploration-behaviour. In particular, we hypothesise that greater efficiency would be associated to shorter duration of the overall exploration stage. However, we consider alternative scenarios, like exploration duration remaining unaltered as a consequence of greater effectiveness requiring the use of an extra time to learn the disposition and relationships between a greater number of obstacles. Noordzij, Zuidhoek, and Postma (2006) suggest that both late and early blind people benefit more from a route description than from a survey description of spaces. In addition, Pasqualotto, Spiller, Jansari, and Proulx (2013) suggest that early blind people tend to produce egocentric representations of the space, while late-blind and sighted people tend to produce allocentric ones. Despite an apparent mismatch between distant exploration and blind people's usual strategies, we hypothesise that adoption of distant exploration does not have a detrimental impact on quality or usefulness of the resulting cognitive maps. Finally, we also hypothesise that a distant-exploration configuration with greater scope and lesser degrees of freedom performs better than the reciprocal configuration. The former configuration is known as flat spotlight (fFoA) while the latter one is known as the spherical spotlight (sFoA). Proximity exploration is referred to as noFoA. The rest of the paper is structured as follows: section two describes the methodology used during the study; section three summarizes the results; section four explores their significance; and section five presents the main conclusions of the study.

2. Methodology

Section 2.1. holds a description of the variables of the study. Section 2.2. holds a description of the system used to collect data. Finally, section 2.3. holds a description of the study design and protocol.

2.1. Variables

Variables in Table 1 were assessed for three different exploration configurations (FoA): one configuration of proximity exploration (noFoA) and two different configurations of distant exploration (fFoA and sFoA).

2.1.1. Exploration process

Effectiveness of the exploration process was defined as the total number of obstacles (both structures and objects) detected during the exploration of a virtual room. The greater the number of obstacles detected, the more effective the exploration process.

On the other hand, efficiency of the exploration process was measured via the duration of the discovery stage (i.e. discovery time). Discovery time is the amount of time from which all the obstacles that are detected (both structures and objects) have already been previously detected during a given exploration session. Beware of the fact that this definition does not mean that all the obstacles in the scene were detected during the discovery stage, but just a maximum number of them, which can be lower than the total number of obstacles in the scene.

The duration of the exploration process is modelled as the total amount of time spent on exploring a virtual room.

Finally, extra time is the amount of time since the end of the discovery stage till the end of the overall exploration process.

2.1.2. Quality of cognitive maps

Quality of cognitive maps was assessed with two variables, namely, overall quality and fluency of the participants to remember their content.

Overall quality was modelled as a score for the deviations of cognitive-map externalizations from the original scene. Said score was computed as the Mahalanobis distance of two four-dimensional vectors where the original scene is represented by (0, 0, 0, 0) coordinates. The lower the deviation value, the better the cognitive-map quality. The description of these four dimensions is as follows:

1. *Identification error*: it represents the error committed by a participant while remembering which obstacles were present in the scene during exploration. Within this context, obstacles are modelled as a nominal variable with three levels, namely, correct identifications, omissions, and insertions. Correct identifications are obstacles present in the original scene and so identified; omissions are obstacles present in the scene but identified as not present, while insertions are obstacles not present in the scene but identified as present.

The identification error was then computed as the normalized sum of omissions and insertions, as shown in Equation (1).

$$\textit{Identification error} = (\textit{total omissions} + \textit{total insertions})/\textit{total number of obstacles} \quad (1)$$

2. *Location error for structures*: it represents the error committed by a participant while identifying the empty room in the original scene. It was modelled as a dichotomous variable and was computed by making participants to choose between three scaled models of empty rooms; and then assigning zero when the participant chose well, and assigning one when he did not. See Equation (2).

$$\textit{location error for structures} = 0\ (\textit{if model choice} = \textit{success})\ \textit{OR location error for structures} = 1\ (\textit{if model choice} = \textit{failure}) \quad (2)$$

3. *Absolute-location error for objects*: it represents the error committed by a participant when placing, in a scaled model of the room, miniatures of correct identifications. Each miniature was represented by a duple of the form (distance, angle). Each component of the duple was modelled as a dichotomous variable. A value of zero was assigned to distance when the corresponding polar coordinate (i.e. rho) of the miniature position was correct, and a value of one when it was not; analogously, a value of zero was assigned to angle when the corresponding polar coordinate (i.e. phy) of the miniature position was correct, and a value of one when it was not. See Equation 3(a) and Equation 3(b).

$$\textit{distance}_i = 0\ (\textit{if model-rho}_i = \textit{schene-rho}_i)\ \textit{OR distance}_i = 1\ (\textit{if model-rho}_i \neq \textit{scene-rho}_i) \quad (3a)$$

$$\textit{angle}_i = 0\ (\textit{if model-phi}_i = \textit{scene-phi}_i)\ \textit{OR angle}_i = 1\ (\textit{if model-phi}_i \neq \textit{scene-phi}_i) \quad (3b)$$

The absolute-location error for objects was then computed as the sum of distance elements from all correct identifications plus the sum of angle elements from all correct identifications, all of it normalized by twice the number of correct identifications. See Equation (4).

Table 1
Variables assessed in the study.

Exploration process				Quality of cognitive maps		Usefulness of cognitive maps
effectiveness	efficiency	duration	Extra time	content	fluency	Success in real tasks

$$absoluteLocation\ error = (distance_i + angle_i)/(2 ^{*} correct\text{-}Identifications) \quad (4)$$

4. *Relative-location error for objects*: it represents the error committed by a participant in the relative location of pairs of correct-identification miniatures. Each pair of miniatures was modelled as a dichotomous variable. A value of zero was assigned when the relative location of those two miniatures was equivalent to the relative position of the corresponding objects in the original scene; a value of one was otherwise assigned. See Equation (5).

$$pairScore_j = 0\ (if\ model\text{-}relativeLocation_j = scene\text{-}relativeLocation_j)\ OR\ pairScore_j = 1\ (if\ model\text{-}relativeLocation_j \neq scene\text{-}relativeLocation_j) \quad (5)$$

The relative-location error for objects was then computed as the sum of pair-scores, normalized by the number of correct-identification pairs. See Equation (6).

$$relateiveLocation\ error = (pairScore_j)/\ correct\text{-}Identification\ pairs \quad (6)$$

Each dimension ranges from zero to one. Thus, the maximum deviation may be computed as the Mahalanobis distance between (0, 0, 0, 0) and (1, 1, 1, 1). The maximum deviation has a value of 9.79.

Finally, fluency to remember the content of cognitive maps was modelled as the time spent building a model of the previously explored room. The lower the time spent the more fluent the participant was.

2.1.3. Usefulness of cognitive maps

Participants were asked to complete three types of tasks in the real equivalent of the previously explored virtual room.

1. *Egocentric task*: during an egocentric task participants must walk from the initial exploration point to a target object; thus, such a task assesses usefulness of absolute locations in the map.
2. *Allocentric task*: during an allocentric task, participants must walk from an object to another one; thus, usefulness of relative locations in the map is assessed.
3. *Orientation task*: during an orientation task, participants must walk back to the starting point; thus, this task assesses participants' ability to update their maps while walking through a real room.

Usefulness of cognitive maps was modelled as a dichotomous variable for each type of task. A value of zero represents success and a value of one represents failure.

2.2. The system

2.2.1. Scenarios

Three different virtual rooms representing an office, a pub, and a bedroom, were implemented. Each of these virtual places count with four walls, two windows, a column, and two doors; but the bar that counts with three doors. In addition, each of these spaces contain six objects (See Table 2).

Table 2
List of objects in each room.

Office	Pub	Bedroom
Paper bin	Doorstep	Magazine rack
Drawer	Umbrella stand	Trunk
Chair	Stool	Bedside table
Desk	Bar	Bed
Bookshelves	Dartboard	Closet
Thermostat	Fire extinguisher	Coat rack

2.2.2. Exploration configurations (FoA)

The noFoA configuration for proximity exploration, and the fFoA and sFoA configurations for distant exploration, are responsible for detecting obstacles while participants explore a virtual room. Different FoA configurations show different behaviours:

1. Proximity exploration involves providing blind people with information at the reach of the cane. Thus, the noFoA configuration was modelled as a volume surrounding the avatar, able to provide information regarding the obstacles within a 1 m range before the avatar, a 1 m range to the left and right of the avatar, and along the entire distance between the floor and the ceiling. The noFoA moves jointly with the avatar as the latter walks across the virtual room. It reports the presence of both objects and structures when colliding with them. When an obstacle is detected in front of the avatar, the noFoA makes it stop and reports the type of obstacle. Participants can make the avatar turn left or right to avoid obstacles. When there is no obstacles in front of the avatar anymore, the noFoA reports the event. When an obstacle is detected either to the left or right of the avatar, the noFoA reports its type, but the avatar keeps walking. Again, when there is no obstacles to the left or right of the avatar anymore, the noFoA reports the event. The blind person can make the avatar walk and stop whenever he wants.

Distant exploration involves providing blind people with information beyond the reach of the cane.

2. The sFoA configuration projects a beam along the avatar's line of sight. This beam is shaped as the projection of a sphere of 1 m of diameter on avatar's line of sight. On changes in the direction of the line-of-sight, the sFoA computes collisions between the beam and all the obstacles in the new direction. Type and distance of each detected obstacle is recorded; and information regarding the closest obstacle to the avatar is reported. Participants can sequentially check the complete list of detected obstacles in the current line of sight (both forward or backwards) with the only limitation of reaching a wall, the ceiling or the floor. This configuration is sensitive to changes of direction to the left, right, up, and down while the avatar stays still at a fixed location.
3. The fFoA configuration behaves like the sFoA but (i) the beam is shaped as the projection of a vertical plane before the avatar and perpendicular to its line of sight; it is as wide as the avatar's shoulders and spans along the entire distance between the floor and the ceiling; and (ii) this configuration is sensitive to changes of direction to the left and right, but not up and down.

2.2.3. Implementation

The system was implemented in Unity3D as a video game for Android. It was deployed on a BQ Aquaris E5 running Android 4.4.4 (KitKat). The app requires a smartphone equipped with a gyroscope and a touch screen. The application shows the virtual representation of each room as a first person view of the avatar's point of view. In spite of the fact that visual information is irrelevant for blind people, it is useful for the development process and debugging purposes.

In the case of the noFoA configuration, participants can control the direction of the line of sight, the avatar's walking status (stationary or walking), and the walking direction. Participants can modify the direction of the line of sight by rotating the smartphone to the left or right, either when the avatar is stationary or walking; in the latter case, rotating the smartphone also makes the avatar turn and change walking direction. Participants may change the avatar's walking status by tapping the smartphone touch screen. The avatar always moves forward. The smartphone vibrates once per avatar's step to provide feedback regarding the walking status.

When there is an obstacle within a 2 m range apart from the avatar, in the direction of the line of sight, the noFoA beeps as a pulse train. The tone of each pulse varies according to the obstacle's height (low, medium, high). And the period between pulses decreases as the avatar comes closer to the obstacle. The beeping shuts down as soon as the obstacle gets out of the avatar's line of sight. If the noFoA ends up colliding frontally with an obstacle, it makes the avatar stop and reports the obstacle's type and the fact that it is two steps away. The noFoA reports this information by playing a voice message over the speaker.

When an obstacle collides with the noFoA out of the avatar's line of sight, the noFoA reports the type of obstacle and its location (left or right). When said obstacle is no longer within the range of the noFoA, it reports the fact that there is free way to the left of right. Feedback is provided, once again, by playing a voice message over the speaker.

In the case of the sFoA and fFoA configurations, participants can control the direction of the line of sight. The avatar always remains stationary in its initial location. Participants can modify the direction of the line of sight by rotating the smartphone to the left or right in both cases, and, additionally, up and down in the case of the sFoA configuration. Participants can explore the list of obstacles in the line of sight by sliding a finger up the smartphone touch screen to check the next obstacle away from the avatar; and by sliding a finger down the smartphone touch screen to check the previous obstacle closer to the avatar. Obstacle reports consist of the type of obstacle and its distance to the avatar by playing a voice message over the speaker.

2.3. Study

2.3.1. Design

Three configurations (noFoA, sFoA, and fFoA) were compared to test the hypotheses described in section 1.2.

A within-subjects cross-sectional study was conducted. Eligible subjects were required to fulfil the following inclusion criteria: (i) be over eighteen years old, (ii) suffer total blindness, (iii) have become blind at least two years before the beginning of the study, and (iv) suffer no additional disabilities. Nineteen participants ($m = 50.63$ years old, $sd = 15.17$) were recruited among people affiliated to ONCE (National Organization for Spanish Blind people), workers of the ONCE Foundation, and from the support service for students with disabilities of the Technical University of Madrid. All participants became blind at least seven years before the beginning of the study ($m = 32.31$, $sd = 19.76$). Being this our first approximation to the topic, we decided to limit the duration of the experiment. In order to choose a proper sample size, we managed to preserve the order of magnitude identified in previous proximity-based studies; taking into account the restrictions imposed by the availability of physical spaces and the size of the research team.

Participants were involved in three experiences. During each experience, they explored a different room (office, pub, or bedroom), using a different configuration for each room (noFoa, sFoA, or fFoA). In order to minimize the impact of possible carry-over effects, both room and FoA pairs were randomized, together with the execution sequence, according to the latin square in Table 3.

2.3.2. Protocol

All participants signed an informed consent prior to the beginning of the study. Each participant was involved in three experiences as shown in the latin square in Table 3. Each experience consisted of six stages:

1. *Welcome*: A member of the research team summarized the objectives of the study, and explained the stages of the experience and the usage of the FoA configuration the participant will use during the exploration stage.
2. *Training*: The participant had the opportunity to practice the usage of the FoA in a training virtual room with two windows, two doors, a sofa and a paper bin. Participants were given no time constraints.
3. *Exploration*: The participant explored one of the three virtual rooms (office, pub, or bedroom) using one of the FoA configurations (noFoA, sFoA, or fFoA) as shown in Table 3. They were asked to explore the room until they felt they could describe its structures and the objects in it. They were given no time constraints. The avatar was initially located in a default location close to one of the doors in the room and facing the opposite wall. The exploration began after the participant slided right or left his finger on the touch screen; and ended when the participant notifies the researcher, who was responsible for closing the exploration screen.

During the exploration stage, and for each detected obstacle, the application records the type of obstacle, a timestamp, the participant gesture that triggered the detection, and the distance between the avatar and the obstacle. The log file with this records was automatically stored in a remote server when the researcher closed the exploration screen.

4. *Questionnaire*: After the exploration stage, the participant was requested to tell the number of walls, windows, doors, and columns that he remembered from the exploration stage. Answers were manually collected by a member of the research team.
5. *Model*: The participant was asked to: (i) chose, out of three options, a model representing the empty virtual room explored during the exploration stage, (ii) identify the objects present in the virtual room out of a list of twelve items. Six of them were actually present and six of them were not; and (iii) place the miniatures of the identified objects in the appropriate locations of the model. The whole process was timed up and a photograph of the resulting model was taken at the end of it.
6. *Real spaces*: For the last stage, the participant was driven to the real equivalent of the virtual room. He was placed at the same location and position as the avatar was at the beginning of the exploration stage. Then the participant was asked to complete three tasks: an egocentric one, an allocentric one, and an orientation one.

Table 3
Latin square.

Participant id	First experience	Second experience	Third experience
1	fFoA-office	noFoA-pub	sFoA-bedroom
2	noFoA-bedroom	sFoA-office	fFoA-pub
3	sFoA-pub	fFoA-bedroom	noFoA-office
4	sFoA-bedroom	noFoA-pub	fFoA-office
5	fFoA-pub	sFoA-office	noFoA-bedroom
6	noFoA-office	fFoA-bedroom	sFoA-pub

During this stage a member of the research team tells the participant toward which objects he must walk and take notes of his success or failure in completing the tasks.

3. Results

Table 1, at the beginning of section 2.1, summarizes the variables assessed in this study.

3.1. The exploration process

3.1.1. Effectiveness of the exploration process

Effectiveness of the exploration process was defined as the total number of obstacles (both structures and objects) detected during the exploration of a virtual room. Table 4 summarizes the values of effectiveness for the three configurations under study. Fig. 1 shows a graphical comparison of effectiveness relative to the total number of obstacles in the room.

The dependence of effectiveness with the FoA configuration was assessed with a Friedman test that resulted statistically significant (Friedman chi-squared = 12.59, df = 2, p-value = 0.0018). Pairwise comparison between types of FoA was conducted by applying a Fisher's LSD test with Holm correction. Both the fFoA and the sFoA showed a statistically significant difference with the noFoA. In particular, there is a 24% improvement in the effectiveness of the fFoA compared to proximity exploration (p-value = 0.0006); and a 12% improvement in the effectiveness of the sFoA compared to proximity exploration (p-value = 0.0039). On the other hand, however, the 11% difference between the two distant configurations under study, i.e. fFoA and sFoA, was not found to be statistically significant (p-value = 0.079).

3.1.2. Efficiency of the exploration process

Efficiency was modelled as discovery duration, which was defined in section 2.1.1. Table 5 summarizes the values of discovery duration for the three FoA configurations under study. Fig. 2 shows a graphical comparison of the time spent during discovery with three different FoAs.

The dependence of discovery duration with the type of FoA was assessed with a repeated measures ANOVA, after checking assumptions for this kind of test. Data from all three groups showed a normal distribution according to the Kolmogorov-Smirnov test (see Table 6).

Homoscedasticity was also met as showed by a Levene's test (F = 1.793, df = 2, p = 0.18). A Mauchly's test, however, showed that sphericity was not met (W = 0.532, p = 0.0064); so a Greenhouse-Geisser correction was applied (GGe = 0.68).

This repeated measures ANOVA test resulted statistically significant after Greenhouse-Geisser correction (F = 5.645, df = 2, p = 0.018). Pairwise comparison between types of FoA was conducted by applying a Tukey pairwise comparison test. Distant exploration with the fFoA entails a 53% reduction in discovery duration, compared to proximity exploration (p-value = 0.0027). There is no statistically significant difference between sFoA and proximity exploration (p-value = 0.54), nor between the two configurations of distant exploration, i.e. fFoA and sFoA, (p-value = 0.066). Nonetheless, in the latter case, a trend is observed that must be studied with a sample of greater size.

3.1.3. Exploration duration

Exploration duration was defined in section 2.1.1. Table 7 summarizes the values of exploration duration for the three FoA configurations under study. Fig. 3 shows a graphical comparison of the time spent during exploration with three different FoAs.

The dependence of exploration duration with the type of FoA

Table 4
Effectiveness of the exploration stage.

fFoA	sFoA	noFoA
14.06 (sd = 1.06) 93.73%	12.67 (sd = 2.93) 84.47%	11.33 (sd = 2.32) 76%

Table 5
Duration of the discovery stage.

fFoA	sFoA	noFoA
234.36 s	412.10 s	496.50 s

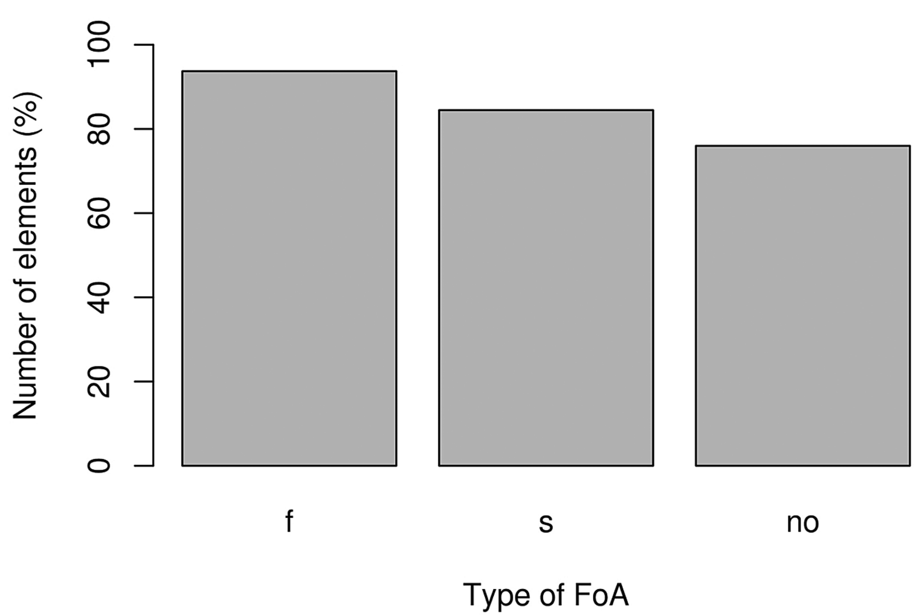

Figure 1. Effectiveness of the exploration stage.

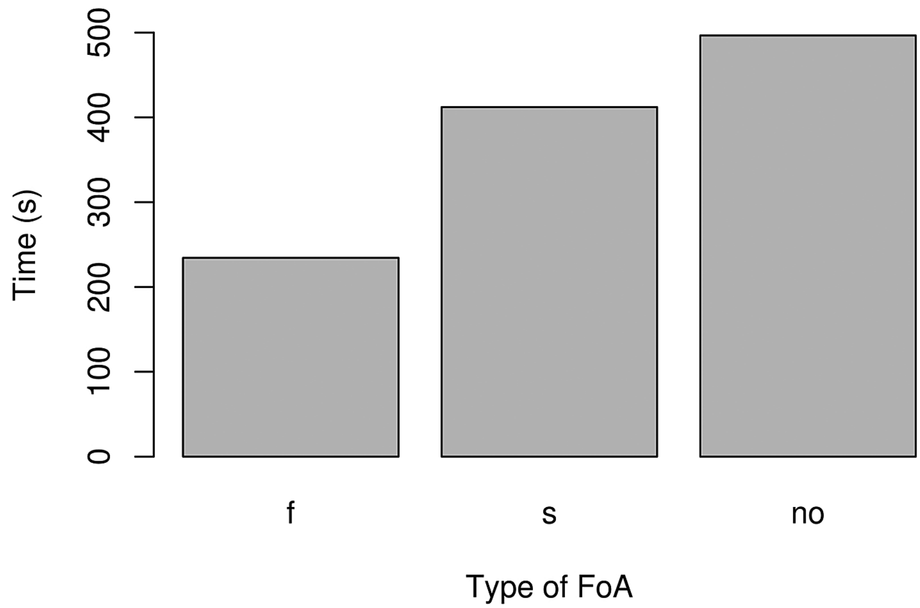

Figure 2. Duration of the discovery stage.

Table 6
Results from Kolmogorov-Smirnov tests (discovery stage).

fFoA	sFoA	noFoA
D = 0.259, p = 0.15	D = 0.266, p = 0.13	D = 0.213, p = 0.34

Table 7
Duration of the exploration stage.

fFoA	sFoA	noFoA
436.15 s	549.74 s	729.80 s

was assessed with a repeated measures ANOVA, after checking assumptions for this kind of test. Data from all three groups showed a normal distribution according to the Kolmogorov-Smirnov test (see Table 8).

Homoscedasticity was also met as showed by a Levene's test (F = 1.37, df = 2, p = 0.26). A Mauchly's test, however, showed that sphericity was not met (W = 0.392, p = 0.00035); so a Huynh-Feldt correction was applied (HFe = 0.645).

This repeated measures ANOVA test resulted not statistically significant after Huynh-Feldt correction (F = 3.452, p-value = 0.067); however, it can be considered that a trend is

Table 8
Results from Kolmogorov-Smirnov tests (exploration stage).

fFoA	sFoA	noFoA
D = 0.300, p = 0.052	D = 0.275, p = 0.093	D = 0.209, p = 0.33

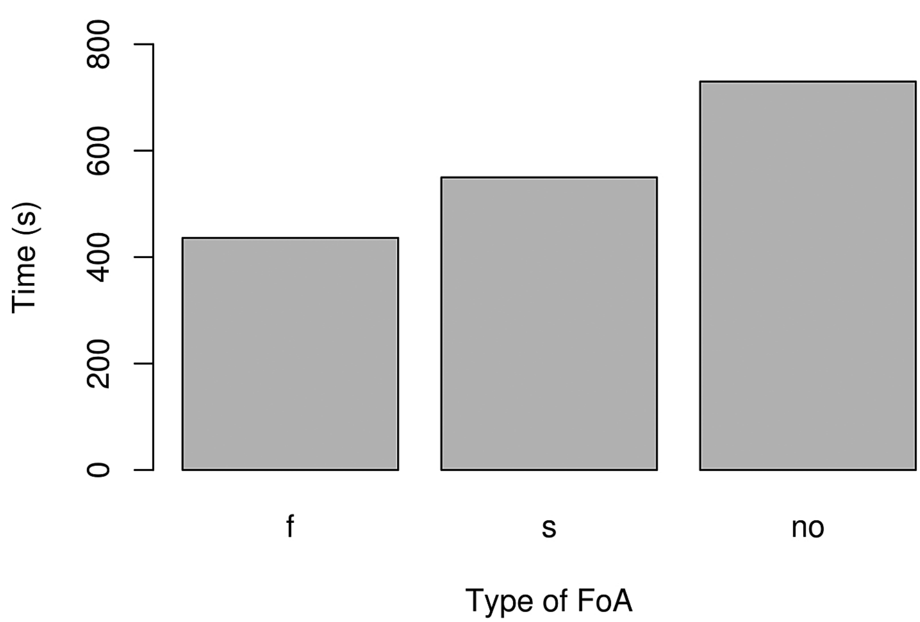

Figure 3. Duration of the exploration stage.

observed, since the p-value is low despite the low power of the sample in use. A post-hoc pairwise comparison was conducted in the form of a Tukey test (read [Games, 1971] in order to find an explanation for the justification of a pairwise comparison in case of trends). The Tukey test resulted statistically significant for the 38% reduction obtained by using the fFoA with respect to proximity exploration ($p = 0.024$).

3.1.4. *Extra time*

Extra time was defined in section 2.1.1. After observing the significance of wall-detection effectiveness during the externalization stage (see section 3.2.1.1.), its impact on exploration behaviour was studied. Table 9 summarizes the values of extra duration for two groups, namely, total detection (four walls detected) and partial detection (less than four walls detected). Fig. 4 shows a graphical comparison of the extra time spent during exploration with the two groups.

The dependence of extra time with wall-detection effectiveness was assessed with a two-samples *t*-test, after checking assumptions for this kind of test. Data from both groups showed a normal distribution according to the Kolmogorov-Smirnov test (see Table 10).

Homoscedasticity was also met as showed by a Levene's test ($F = 3.713$, $df = 1$, $p = 0.059$).

Due to the weak strength of said assumptions, besides the parametric two-samples *t*-test ($t = 2.319$, $df = 52$, p-value $= 0.012$), two non-parametric versions of said test were run, namely, a Welch's *t*-test for unequal variances ($t = 3.186$, $df = 51.77$, p-value $= 0.0012$) and a Wilcoxon rank sum test for non-normality ($W = 444$, p-value $= 0.0036$). All three of them resulted statistically significant.

Table 10
Results from Kolmogorov-Smirnov tests (extra time).

Total detection	Partial detection
$D = 0.206$, p-value $= 0.068$	$D = 0.179$, p-value $= 0.62$

3.2. *Quality of cognitive maps*

In order to evaluate the quality of the cognitive maps generated during an exploration, the content of these maps was assessed together with the fluency with which participants were able to remember said content. Deviations from the original scene are computed as the Mahalanobis distance of two four-dimensional vectors (identification error for obstacles, location error for structures, absolute-location error for objects, relative-location error for objects) where the original scene is represented by (0, 0, 0, 0) coordinates. The lower the value of the deviation, the better the quality of the cognitive map. On the other hand, fluency to remember the content of cognitive maps is modelled as the time spent building a model of the previously explored room.

3.2.1. *Overall quality of cognitive maps*

Table 11 summarizes the mean overall quality scores for the three different FoA configurations under study. Please, notice that the score represents the deviation from the original scene. Thus, the lower the value of the score the better the quality of the cognitive map. Fig. 5 shows a graphical comparison of these deviations relative to the maximum deviation.

The dependence of overall quality with the FoA configuration was assessed with a Friedman test that resulted not statistically significant (Friedman chi-squared $= 3.111$, $df = 2$, p-value $= 0.21$). In view of that result, each score-dimension was studied separately;

Table 9
Duration of the extra time.

Total detection	Partial detection
225.58 s	108.56 s

Table 11
Deviation of the content of cognitive maps.

fFoA	sFoA	noFoA
3.32	3.35	3.70
34%	35%	38%

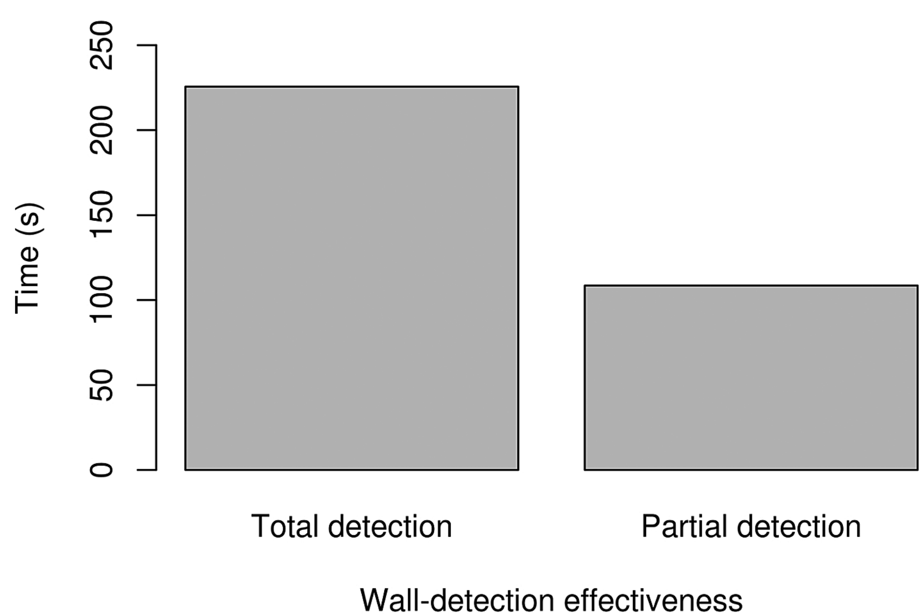

Figure 4. Duration of the extra time.

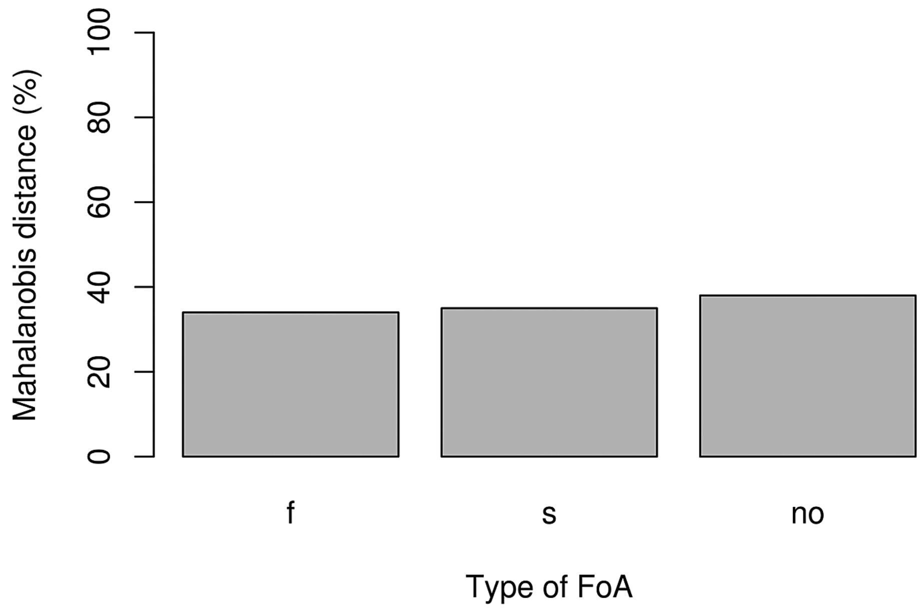

Figure 5. Deviation of the content of cognitive maps.

and none of them showed a dependence with the type of FoA:

1. In the case of the *identification error*, obstacles were modelled as a nominal variable with three levels, namely, correct identifications, omissions, and insertions. Its dependence with the type of FoA was assessed with a Mantel-Haenszel test of general association (Cochran-Mantel-Haenszel M^2 = 5.598, df = 4, p-value = 0.23).
2. In the case of the *location error for structures*, success in model choice was modelled as a dichotomous variable. Its dependence with the type of FoA was assessed with a Cochran-Mantel-Haenszel test for general association (Cochran-Mantel-Haenszel M^2 = 1.6, df = 2, p-value = 0.45).
3. In the case of the *absolute-location error for objects*, the error values ware modelled as an ordinal variable with four levels. A level for deviations lower than 25%, another level for deviations between 25% and 50%, another level for deviations between 50% and 75%, and a level for deviations over 75%. The dependence of this variable with the type of FoA was assessed with a Mantel-Haenszel mean score test (chisq = 0.0377, df = 2, p-value = 0.98).
4. In the case of the *relative-location error for objects*, the error values were modelled as an ordinal variable with the same levels as the previous dimension. The dependence of this variable with the type of FoA was assessed with a Mantel-Haenszel mean score test (chisq = 2.657, df = 2, p-value = 0.26).

The absence of dependence in the case of the identification error was particularly intriguing because effectiveness of obstacle detection during an exploration did show a dependence with the type of exploration (see section 3.1.1.); so the reasons why the identification dimension does not preserve this dependence were studied more carefully. The dependence of detection status and identification status with the type of FoA was studied separately for walls, windows, and objects.

3.2.1.1. Walls. Both the detection and identification statuses of walls were modelled as dichotomous variables. In the case of detection status, walls can count either as detected or missing. In the case of identification status, they can count as either identified or omitted (see Fig. 6).

The dependences of both detection and identification statuses

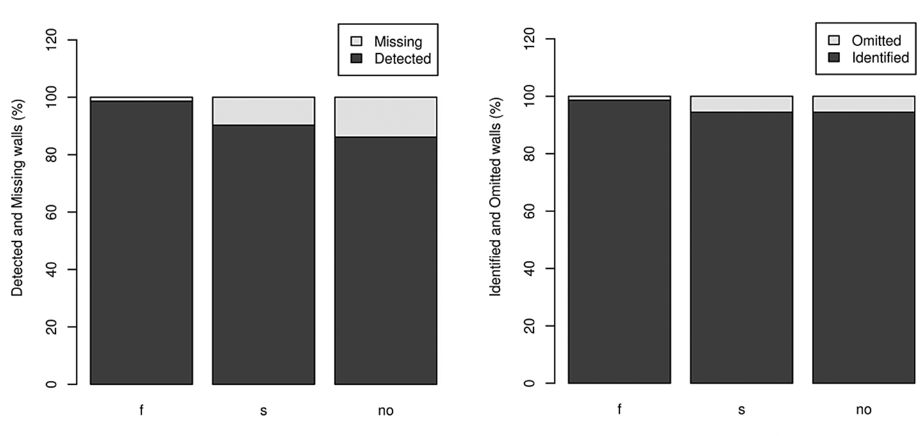

Figure 6. Detection of walls (left) vs. Identification of walls (right).

with the type of FoA were assessed each with a Mantel-Haenszel test of general association, which resulted significant in the case of detection status (Cochran-Mantel-Haenszel Mˆ2 = 7.787, df = 2, p-value = 0.02); but not significant for identification status (Cochran-Mantel-Haenszel Mˆ2 = 2.176, df = 2, p-value = 0.34).

In particular, while the fFoA shows perfect reciprocation between fully correct detections (i.e. detecting four walls during exploration) and fully correct identifications (i.e. identifying four walls during the post-exploration interview); in the case of both sFoA and noFoA configurations, there are more fully correct identifications than fully correct detections. The dependence of both fully correct detections and fully correct identifications with the FoA configuration was assessed by modelling both of them as dichotomous variables and executing two Mantel-Haenszel tests of general association, which resulted significant in the case of fully correct detections (Cochran-Mantel-Haenszel Mˆ2 = 8.6, df = 2, p-value = 0.014); but not significant in the case of fully correct identifications (Cochran-Mantel-Haenszel Mˆ2 = 3.6, df = 2, p-value = 0.17).

In view of this result, the attributable risk relationship between fully correct identifications and fully correct detections was studied. The result shows that 75% of fully correct identifications are independent of the number of walls detected during exploration.

3.2.1.2. Windows. Both the detection and identification statuses of windows were modelled in a similar way to the case of walls (See Fig. 7).

Their dependences with the type of FoA were assessed each with a Mantel-Haenszel test of general association which resulted significant for detection status (Cochran-Mantel-Haenszel Mˆ2 = 11.395, df = 2, p-value = 0.0034); but not significant for identification status (Cochran-Mantel-Haenszel Mˆ2 = 0.345, df = 2, p-value = 0.84).

3.2.1.3. Objects. Both the detection and identification statuses of objects were modelled in a similar way to the case of walls and windows (See Fig. 8).

Their dependencies with the type of FoA were assessed each with a Mantel-Haenszel test of general association which resulted significant for both detections (Cochran-Mantel-Haenszel Mˆ2 = 21.68, df = 2, p-value = 1.96e-05) and identifications (Cochran-Mantel-Haenszel Mˆ2 = 9.500, df = 2, p-value = 0.0087).

3.2.2. Fluency

Fluency to remember the content of cognitive maps, was modelled as the time spent building a model of the previously explored room. The lower the time, the more fluent the participant was. Table 12 summarizes the values for the three different types of FoA under study. Fig. 9 shows a graphical comparison of said values.

The dependency of fluency with the type of FoA was assessed with a repeated measures ANOVA, after checking assumptions for this kind of test. Data from all three groups showed a normal distribution according to the Kolmogorov-Smirnov test (see Table 13).

Homoscedasticity was also met as showed by a Levene's test

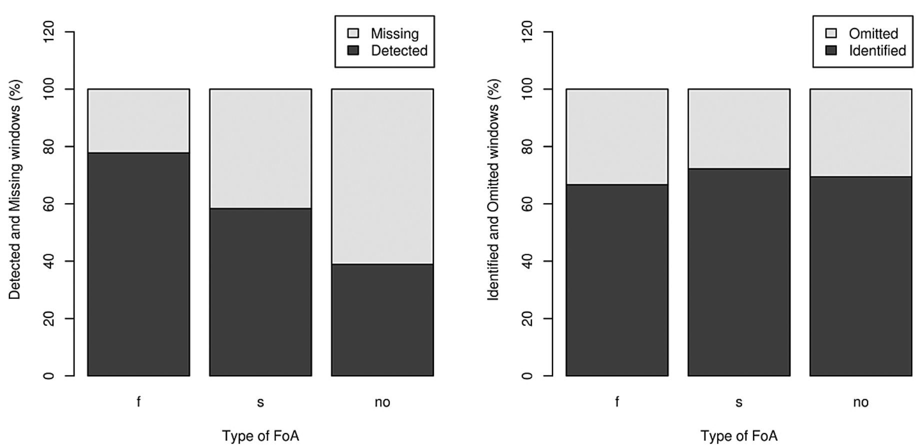

Figure 7. Detection of windows (left) vs. Identification of windows (right).

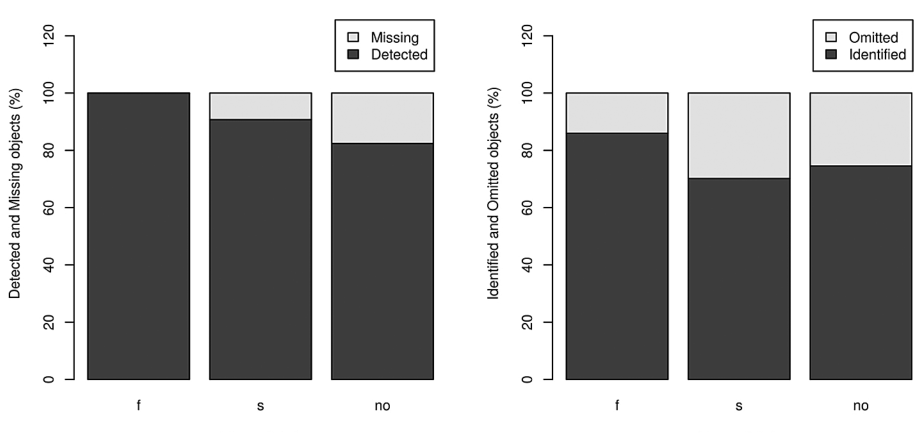

Figure 8. Detection of objects (left) vs. Identification of objects (right).

Table 12
Duration of the model building stage.

fFoA	sFoA	noFoA
4 min 9 s	3 min 34 s	3 min 56 s

Table 13
Results from Kolmogorov-Smirnov tests (fluency).

fFoA	sFoA	noFoA
D = 0.162, p = 0.64	D = 0.221, p = 0.27	D = 0.221, p = 0.27

($F = 0.193$, $df = 2$, $p = 0.82$). A Mauchly's test showed that sphericity was also met ($W = 0.852$, $p = 0.26$); so no correction was necessary for the results of the repeated measures ANOVA test; which resulted not statistically significant ($F = 1.144$, $p = 0.33$).

3.3. *Usefulness of cognitive maps*

To evaluate the usefulness of the cognitive maps generated during a virtual visit, success on completing three types of tasks in the real equivalent of the virtual room was assessed. Egocentric, allocentric and orientation tasks were assessed (See Fig. 10).

Success was modelled as a dichotomous variable for each type of task. The dependence of success with the type of FoA was assessed with a Mantel-Haenszel test of general association for each type of task which resulted not significant for all of them. In the case of egocentric tasks (Cochran-Mantel-Haenszel $M^2 = 2.889$, $df = 2$, p-value = 0.24); in the case of allocentric tasks (Cochran-Mantel-Haenszel $M^2 = 0.545$, $df = 2$, p-value = 0.76); and in the case of orientation tasks (Cochran-Mantel-Haenszel $M^2 = 0.222$, $df = 2$, p-value = 0.89).

The relationship between success status of real tasks and quality of the cognitive maps was studied. The mean overall quality scores of cognitive maps was computed for both successfully completed tasks and failed tasks (See Fig. 11).

The difference between successfully completed tasks and failures, for different types of tasks, was each assessed with a two-sample *t*-test, after checking assumptions for this kind of test. Data from both groups showed a normal distribution, for all three types of task, according to the Kolmogorov-Smirnov test (see Tables 14 and 15).

Homoscedasticity was met for egocentric and allocentric tasks, but not for orientation ones, as showed by a Levene's test (see Table 15).

Thus, egocentric and allocentric data were assessed with two-sample t-tests, and orientation data was assessed with a Welch's *t*-test for unequal variance. The fact that deviations of successfully completed tasks are lower than deviations of failed tasks resulted statistically significant for egocentric tasks ($t = -1.682$, $df = 46$, p-value = 0.050) and allocentric tasks ($t = -1.923$, $df = 40$, p-value = 0.031); but not for orientation tasks ($t = -0.574$, $df = 14.123$, p-value = 0.58).

4. Discussion

To the best of our knowledge this is the first work using distant exploration and comparing it with proximity exploration.

Evidence supports our initial hypothesis of greater efficacy associated to distant exploration; and, despite the limited sample-power, does so with a rather strong statistical significance (in the case of the flat spotlight the effectiveness rise reaches 24% with p-value = 0.0006). In spite of showing better effectiveness, the identification error dimension in the quality score did not show differences for different types of FoA. Although a deterioration in the conversion of object detections into identifications is observed for all types of FoA, object identification remains better for the flat spotlight; but in the case of walls and windows, conversion rates do not preserve differences. While overall conversion rate for walls was over 100% for all types of FoA, in the case of windows, different configurations show different behaviours. Proximity exploration and the spherical spotlight showed conversion rates over 100% as well, but the flat spotlight showed a conversion rate below 100%. In addition, an analysis of attributable risk shows that 75% of the time, participants reported the correct number of walls regardless how many of them they actually detected during exploration. We interpret it as blind people tending to rely on their preconceived ideas regarding the usual structure of a room. In particular, the idea

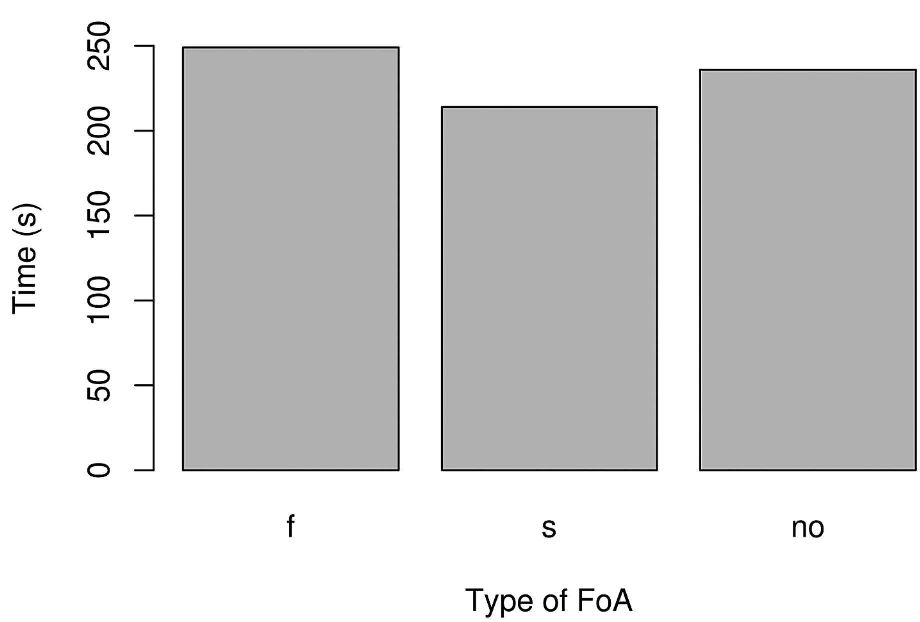

Figure 9. Duration of the model building stage.

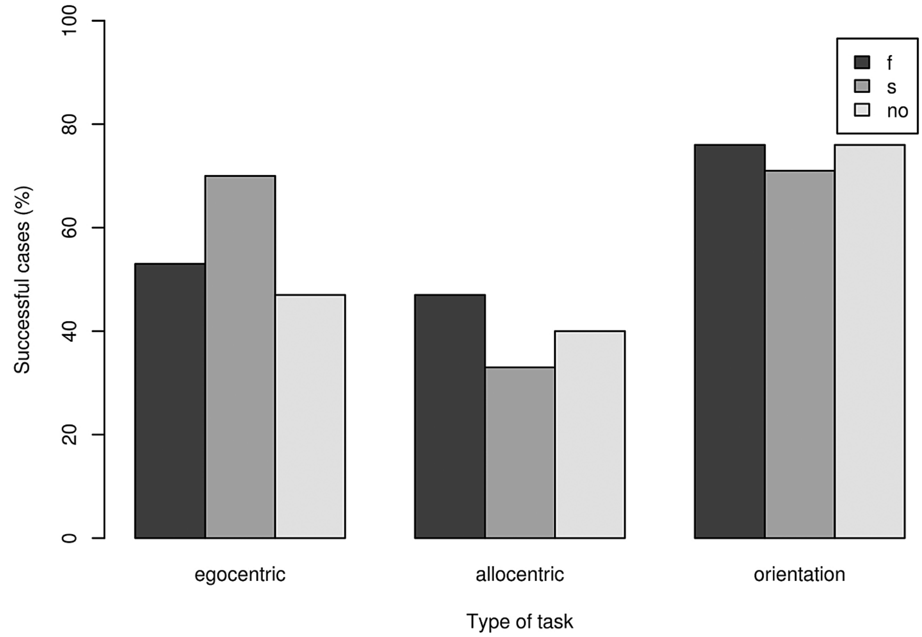

Figure 10. Distribution of successfully completed task.

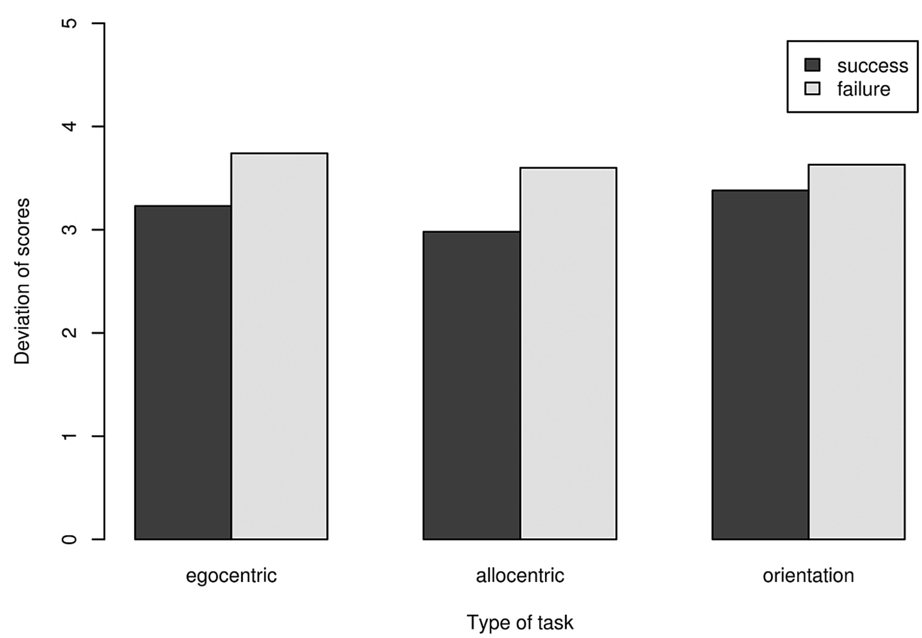

Figure 11. Mean deviation scores for different success status and type of task.

Table 14
Results from Kolmogorov-Smirnov tests (success vs. failure).

	Success	Failure
egocentric	D = 0.0743, p-value = 0.99	D = 0.128, p-value = 0.86
Allocentric	D = 0.0943, p-value = 0.99	D = 0.179, p-value = 0.36
orientation	D = 0.108, p-value = 0.76	D = 0.130, p-value = 0.97

Table 15
Results from Levene's tests (success vs. failure).

egocentric	F = 3.040, df = 1, p = 0.088
allocentric	F = 0.007, df = 1, p = 0.93
orientation	F = 4.203, df = 1, p = 0.046

of rooms having four walls is particularly strong. Additional studies, where virtual rooms show a wider variety of walls configurations, could be useful to confirm this point.

Evidence also confirmed that, together with this rise in effectiveness, distant exploration was also associated with a greater efficiency. Again, despite the limited sample-power, good statistical significance was observed (in the case of the flat spotlight reduction in discovery time reaches 53% with p-value = 0.0027). Distant exploration, therefore, allowed blind people to detect a greater number of obstacles while spending less time in the process. We assumed that the impact of efficiency and the impact of effectiveness on exploration behaviour would point in opposite directions. While greater efficiency would foster shorter exploration stages, greater effectiveness would require the use of extra time to learn the disposition and relationships between a greater number of obstacles. Although statistical significance is not strong enough (p-value = 0.067), evidence suggests that distant exploration might indeed be associated to a reduction in the duration of the exploration stage (pairwise comparison in the case of the flat spotlight showed a reduction reaching 38% with p-value = 0.024). In spite of the effects of low sample-power increasing the probability of extreme results, type I error remains low. In addition, low power also increases the probability of making a mistake by not rejecting the null hypothesis. Thus, we think that chances of a larger sized study corroborating the reduction in exploration time, are high.

A dependence of the extra time after the end of the discovery stage with wall detection was observed (p-value = 0.012); supporting the hypothesis of previously-observed preconceived-ideas having an impact on exploration behaviour. Extra time was in fact longer when blind people detected all the four walls. We interpret it as follows: once blind people detected the expected number of walls, the absence of novel obstacle detections was interpreted as a sign of achievement; and some extra time was spent on improving knowledge about layout disposition. On the other hand, as long as wall detections did not reach the expected value, the absence of novel obstacle detections was interpreted as a waste of time; and led them to quit exploration.

No differences were observed for cognitive-map quality between different types of FoA. Although in line with our initial hypothesis (i.e. changes from distant exploration do not have a detrimental impact on cognitive-map quality) mean scores are worse than expected. Identification error remains reasonably low, so the location errors rise as the source of discrepancy. The novelty of the distant exploration paradigm suggests that blind people might need longer training periods to better capture the nature of information regarding obstacle location; but the fact that proximity exploration was designed to resemble the act of walking around a physical room, suggests that additional underlying factors, like suboptimal feedback configurations, might be present. Limitations imposed by the study design did not allow us to explore these hypotheses.

Success in egocentric and allocentric tasks shows, regardless the type of exploration, a dependence with deviation scores. No dependence is observed for orientation tasks. Orientation tasks are the result of physically walking around the real room and they help to update blind people's cognitive map regardless the previous exploration configuration; which also explains the greater number of successful orientation tasks. No differences were observed in the usefulness of cognitive maps for different types of exploration in any of the three types of tasks. This result is consistent with the fact that no dependence was found between the quality of cognitive maps and the type of exploration.

A trend is observed for the flat spotlight being 11% more effective (p-value = 0.079) and 21% more efficient (p-value = 0.0659) than the spherical spotlight. Again, in spite of the effects of low sample-power increasing the probability of extreme results, type I error remains low. In addition, low power also increases the probability of making a mistake by not rejecting the null hypothesis. Thus, we think that chances of a larger sized study corroborating the improvement in effectiveness and efficiency, are high.

In their proximity exploration study, Lahav and Mioduser (2004) report mean exploration times of 30 min for a room of similar size and complexity than our three spaces. Said mean exploration times are considerably longer than those found in our study (fFoa = 7 min, sFoA = 9 min, noFoA = 12 min). The main difference in proximity exploration mechanisms between the two studies was that, while in the former one, participants had to identify obstacles by learning their shape via haptic feedback, in our study, obstacle functionality was directly reported by the feedback interface via voice messages. Obstacle identifications in our study are similar or better than those reported in Lahav and Mioduser (2008a): objects (84% vs. fFoA = 86%, sFoA = 70%, noFoA = 75%), windows (25% vs. fFoA = 67%, sFoA = 72%, noFoA = 69%), doors (46% vs. fFoA = 74%, sFoA = 73%, noFoA = 74%), and columns (48% vs. fFoA = 59%, sFoA = 71%, noFoA = 41%); they do not report figures for wall detection. There is a difference between their reported successful model-choice (95%) and those found in our study (fFoA = 56%, sFoA = 67%, noFoA = 50%). The main difference in model-choice stage between the two studies was that the former one offered three options with different shapes and sizes, while in our study shape and sizes remain the same and changes are observable in the disposition of doors and windows only. They also report better location of miniatures within the models (46% vs. fFoA = 31%, sFoA = 30%, noFoA = 25%) however somewhat low compared to success in real tasks: egocentric (81% vs. fFoA = 56%, sFoA = 67%, noFoA = 50%), allocentric (71% vs. fFoA = 50%, sFoA = 33%, noFoA = 44%) (Lahav & Mioduser, 2008b). We interpret it as a manifestation of the previously discussed effect of cognitive map updating during physical exploration of the room. Other previous studies did not use spaces of comparable size and complexity.

Coming from a within-subjects design, our study results are well suited to remove individual differences among the participants as a source of error. However, since none of the variables is related to time, they are susceptible to adverse carry-over effects. This circumstance was addressed by applying the latin square in section 2.3.1. However, it has to be noted that the reduced sample size of the study can reduce the power of said randomization to control carry-over effects. Being this study our first approximation to the topic, we decided to limit the duration of the experiment. In order to choose a proper sample size, we managed to preserve the order of magnitude identified in previous proximity-based studies; taking into account the restrictions imposed by the availability of physical spaces and the size of the research team. A study with a larger sample and a between-subjects design would be appropriate to address said drawbacks.

5. Conclusions

Visits to simulations of real spaces in virtual reality have been proposed as a means for blind people to gain spatial knowledge of a place before actually visiting it. Within this paper we studied the differences between two different exploration approaches: distant and proximity exploration. We hypothesised that distant exploration improves efficacy and efficiency of the exploration process. Then, we hypothesised that greater efficiency would be associated to shorter duration of the overall exploration stage. We also hypothesised that changes during exploration do not have a detrimental impact on quality or usefulness of the resulting cognitive maps. Finally, we hypothesised that, in the case of distant exploration, a flat spotlight performs better than a spherical spotlight. After completion of our study we reached the following conclusions.

Distant exploration is associated with greater effectiveness during the exploration stage (i.e. more obstacles are detected than with proximity exploration). However, said difference is not preserved during the externalization stage. This discrepancy is a sign of blind people tending to rely on their preconceived ideas regarding the usual structure of a room. In particular, the idea of rooms having four walls is particularly strong.

Distant exploration is associated with shorter duration of the discovery stage (i.e. less time is necessary to detect obstacles for the first time) and with shorter duration of the overall exploration stage. Statistical significance of the later one is weak; but a study with a larger sample size has good chances of corroborating the result.

Wall-detection effectiveness drives behaviour during the exploration stage. Once blind people detect the expected number of walls, the absence of novel obstacle detections is interpreted as a sign of achievement; and some extra time is spent on improving knowledge about layout disposition. On the other hand, as long as wall detections do not reach the expected value, the absence of novel obstacle detections is interpreted as a waste of time; and leads them to quit exploration.

Limitations imposed by the study design did not allow us to look for the factors that affect cognitive-map quality scores. Duration of the training periods and feedback configurations are suggested as potential candidates.

Cognitive-map quality-scores are related to task success for egocentric and allocentric tasks.

A distant-exploration configuration with greater scope and lesser degrees of freedom (flat spotlight) might perform better than the reciprocal configuration (spherical spotlight) but further studies are necessary to corroborate this result.

The within-subjects nature of our study makes variables susceptible to adverse carry-over effects; and the sample size may not be big enough for the latin-square randomization to control for these effects. A study with a larger sample and a between-subjects design would be appropriate to address said drawbacks.

6. Declaration of interest

All authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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References

de Almeida Vasconcellos, R. A., & Tsuji, B. (2005). Chapter 18 Interactive mapping for people who are blind or visually impaired. In D. R. F. Taylor (Ed.), *Modern cartography series, CybercartographyTheory and practice* (pp. 411–431). Academic Press. http://dx.doi.org/10.1016/S1363-0814(05)80021-8.

Andrews, S. K. (1983). Spatial cognition through tactual maps. In *Proceedings of the 1st international symposium on maps and graphics for the visually handicapped* (pp. 30–40). Washington, DC: Association of American Geographers.

Bartyna, W., Ambroszkiewicz, S., Faderewski, M., Jakubowski, S., Kocieliński, D., Mikułowski, D., et al. (2005). Blind-enT: Making objects visible for blind people. International congress series, vision 2005. In *Proceedings of the international congress held between 4 and 7 april 2005 in london, UK 1282* (pp. 974–979). http://dx.doi.org/10.1016/j.ics.2005.05.075.

Campos, M., de, B., Sánchez, J., Martins, A. C., Santana, R. S., & Espinoza, M. (2014). Mobile navigation through a science museum for users who are blind. In *Universal access in human-computer interaction. Aging and assistive environments. Presented at the international conference on universal access in human-computer interaction* (pp. 717–728). Cham: Springer. http://dx.doi.org/10.1007/978-3-319-07446-7_68.

Connors, E. C., Chrastil, E. R., Sánchez, J., & Merabet, L. B. (2014). Virtual environments for the transfer of navigation skills in the blind: A comparison of directed instruction vs. video game based learning approaches. *Front. Hum. Neurosci., 8*. http://dx.doi.org/10.3389/fnhum.2014.00223.

Games, P. A. (1971). Multiple comparisons of means. *American Educational Research Journal, 8*, 531–565. http://dx.doi.org/10.3102/00028312008003531.

Giraud, S., Brock, A. M., Macé, M. J.-M., & Jouffrais, C. (2017). Map learning with a 3D printed interactive small-scale Model: Improvement of space and text memorization in visually impaired students. *Front. Psychol., 8*. http://dx.doi.org/10.3389/fpsyg.2017.00930.

Golledge, R. G., Klatzky, R. L., & Loomis, J. M. (1996). Cognitive mapping and wayfinding by adults without vision. In J. Portugali (Ed.), *The construction of cognitive maps, GeoJournal library* (pp. 215–246). Netherlands: Springer. http://dx.doi.org/10.1007/978-0-585-33485-1_10.

Kaiser, E. B., & Lawo, M. (2012). Wearable navigation system for the visually impaired and blind people. In *2012 IEEE/ACIS 11th international conference on computer and information science. Presented at the 2012 IEEE/ACIS 11th international conference on computer and information science* (pp. 230–233). http://dx.doi.org/10.1109/ICIS.2012.118.

Kitchin, R. M. (1994). Cognitive maps: What are they and why study them? *Journal of Environmental Psychology, 14*, 1–19. http://dx.doi.org/10.1016/S0272-4944(05)80194-X.

Kitchin, R. (2001). Cognitive maps. In N. J. Smelser, & P. B. Baltes (Eds.), *International encyclopedia of the social & behavioral sciences* (pp. 2120–2124). Oxford: Pergamon. http://dx.doi.org/10.1016/B0-08-043076-7/02531-6.

Kitchin, R. M., Blades, M., & Golledge, R. G. (1997). Understanding spatial concepts at the geographic scale without the use of vision. *Progress in Human Geography, 21*, 225–242. http://dx.doi.org/10.1191/030913297668904166.

Kitchin, R. M., & Jacobson, R. D. (1997). Techniques to collect and analyze the cognitive map knowledge of persons with visual impairment or Blindness: Issues of validity. *Journal of Visual Impairment & Blindness, 91*, 360–376.

Knight, H. (2012). Robot sensing and smartphones help blind navigate. *New Scientist, 214*, 19. http://dx.doi.org/10.1016/S0262-4079(12)61075-6.

Lahav, O., & Mioduser, D. (2004). Exploration of unknown spaces by people who are blind using a multi-sensory virtual environment. *Journal of Special Education Technology, 19*, 15–23. http://dx.doi.org/10.1177/016264340401900302.

Lahav, O., & Mioduser, D. (2008a). Construction of cognitive maps of unknown spaces using a multi-sensory virtual environment for people who are blind. *Computers in Human Behavior, 24*, 1139–1155. http://dx.doi.org/10.1016/j.chb.2007.04.003.

Lahav, O., & Mioduser, D. (2008b). Haptic-feedback support for cognitive mapping of unknown spaces by people who are blind. *International Journal of Human-computer Studies, 66*, 23–35. http://dx.doi.org/10.1016/j.ijhcs.2007.08.001.

Lahav, O., Schloerb, D. W., Kumar, S., & Srinivasan, M. A. (2008). BlindAid: A learning environment for enabling people who are blind to explore and navigate through unknown real spaces. In *2008 virtual rehabilitation. Presented at the 2008 virtual rehabilitation* (pp. 193–197). http://dx.doi.org/10.1109/ICVR.2008.4625159.

Lahav, O., Schloerb, D., Kumar, S., & Srinivasan, M. (2012). A virtual environment for people who are blind – a usability study. *Jnl of Assistive Technologies, 6*, 38–52. http://dx.doi.org/10.1108/17549451211214346.

Lahav, O., Schloerb, D. W., & Srinivasan, M. A. (2015). Rehabilitation program integrating virtual environment to improve orientation and mobility skills for people who are blind. *Computers & Education, 80*, 1–14. http://dx.doi.org/10.1016/j.compedu.2014.08.003.

Loomis, J. M., Klatzky, R. L., & Giudice, N. A. (2013). Representing 3D space in working Memory: Spatial images from vision, hearing, touch, and language. In *Multisensory imagery* (pp. 131–155). New York, NY: Springer. http://dx.doi.org/10.1007/978-1-4614-5879-1_8.

Maidenbaum, S., Buchs, G., Abboud, S., Lavi-Rotbain, O., & Amedi, A. (2016). Perception of graphical virtual environments by blind users via sensory substitution. *PLoS One, 11*, e0147501. http://dx.doi.org/10.1371/journal.pone.0147501.

Merabet, L. B., Connors, E. C., Halko, M. A., & Sánchez, J. (2012). Teaching the blind to find their way by playing video games. *PLoS One, 7*, e44958. http://dx.doi.org/10.1371/journal.pone.0044958.

Merabet, L. B., & Sánchez, J. (2016). Development of an audio-haptic virtual interface for navigation of large-scale environments for people who are blind. In *Universal access in human-computer interaction. Users and context diversity. Presented at the international conference on universal access in human-computer interaction* (pp. 595–606). Cham: Springer. http://dx.doi.org/10.1007/978-3-319-40238-3_57.

Noordzij, M. L., Zuidhoek, S., & Postma, A. (2006). The influence of visual experience on the ability to form spatial mental models based on route and survey descriptions. *Cognition, 100*, 321–342. http://dx.doi.org/10.1016/j.cognition.2005.05.006.

Papadopoulos, K., Koustriava, E., & Barouti, M. (2017). Cognitive maps of individuals with blindness for familiar and unfamiliar spaces: Construction through audio-tactile maps and walked experience. *Computers in Human Behavior, 75*, 376–384. http://dx.doi.org/10.1016/j.chb.2017.04.057.

Pasqualotto, A., Spiller, M. J., Jansari, A. S., & Proulx, M. J. (2013). Visual experience facilitates allocentric spatial representation. *Behavioural Brain Research, 236*, 175–179. http://dx.doi.org/10.1016/j.bbr.2012.08.042.

Picinali, L., Afonso, A., Denis, M., & Katz, B. F. G. (2014). Exploration of architectural spaces by blind people using auditory virtual reality for the construction of spatial knowledge. *International Journal of Human-computer Studies, 72*, 393–407. http://dx.doi.org/10.1016/j.ijhcs.2013.12.008.

Punwilai, J., Noji, T., & Kitamura, H. (2009). The design of a voice navigation system for the blind in Negative Feelings Environment. In *2009 9th international symposium on communications and information technology. Presented at the 2009 9th international symposium on communications and information technology* (pp. 53–58). http://dx.doi.org/10.1109/ISCIT.2009.5341288.

Rieser, J. J., Guth, D. A., & Hill, E. W. (1982). Mental processes mediating independent travel: Implications for orientation and mobility. *Journal of Visual Impairment & Blindness, 76*, 213–218.

Sanchez, J. H., Aguayo, F. A., & Hassler, T. M. (2007). Independent outdoor mobility for the blind. In *2007 virtual rehabilitation. Presented at the 2007 virtual rehabilitation* (pp. 114–120). http://dx.doi.org/10.1109/ICVR.2007.4362150.

Tinti, C., Adenzato, M., Tamietto, M., & Cornoldi, C. (2006). Visual experience is not necessary for efficient survey spatial cognition: Evidence from blindness. *The Quarterly Journal of Experimental Psychology, 59*, 1306–1328. http://dx.doi.org/10.1080/17470210500214275.

Tolman, E. C. (1948). Cognitive maps in rats and men. *Psychological Review, 55*, 189–208. http://dx.doi.org/10.1037/h0061626.

Wang, Z., Li, N., & Li, B. (2012). Fast and independent access to map directions for people who are blind. *Interact Comput, 24*, 91–106. http://dx.doi.org/10.1016/j.intcom.2012.02.002.

Xie, Y., Bigelow, R. T., Frankenthaler, S. F., Studenski, S. A., Moffat, S. D., & Agrawal, Y. (2017). Vestibular loss in older adults is associated with impaired spatial Navigation: Data from the triangle completion task. *Front. Neurol., 8*. http://dx.doi.org/10.3389/fneur.2017.00173.

Zwiers, M., Opstal, A. V., & Cruysberg, J. (2001). Two-dimensional sound-localization behavior of early-blind humans. *Exp Brain Res, 140*, 206–222. http://dx.doi.org/10.1007/s002210100800.