The Influence of the Encoding Modality on Spatial Navigation for Sighted and Late-Blind People

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Abstract

People usually rely on sight to encode spatial information, becoming aware of other sensory cues when deprived of vision. In the absence of vision, it has been demonstrated that physical movements and spatial descriptions can effectively provide the spatial information that is necessary for the construction of an adequate spatial mental model. However, no study has previously compared the influence of these encoding modalities on complex movements such as human spatial navigation within real room-size environments. Thus, we investigated whether the encoding of a spatial layout through verbal cues — that is, spatial description — and motor cues — that is, physical exploration of the environment — differently affect spatial navigation within a real room-size environment, by testing blindfolded sighted (Experiment 1) and late-blind (Experiment 2) participants. Our results reveal that encoding the environment through physical movement is more effective than through verbal descriptions in supporting active navigation. Thus, our findings are in line with the studies claiming that the physical exploration of an environment enhances the development of a global spatial representation and improves spatial updating. From an applied perspective, the present results suggest that it might be possible to improve the experience for visually impaired people within a new environment by allowing them to explore it.

Keywords

Spatial navigation, encoding modalities, spatial description, physical movement

1. Introduction

In daily life, people commonly learn new environments and new routes by means of a combination of different sources of information. It has been suggested that perception of the landmark location within an environment generally improves with the number of sensory channels involved (Jürgens and

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Becker, 2006). Human sensory channels provide different kinds of information — such as auditory, visual and body-based — useful for the development of an adequate spatial representation. However, people rely mainly on sight to locate objects within the environment and to update their position when moving, becoming aware of other sensory cues when deprived of vision. In this situation, object location and spatial updating can occur on the basis of the remaining internal sensory cues (e.g., body-based information) and of external symbolic cues (e.g., language).

The involvement of sensory and symbolic cues is undeniably important when sight deprivation is irreversible, such as for blind people; indeed, people with visual impairment have to learn to use cues not deriving from sight to move and orient in their surrounding environments. Several studies have reported that body-based information and spatial descriptions can be effective in supporting visually impaired people in their navigation within an environment (e.g., Afonso *et al.*, 2010).

Body-based information refers to the information deriving from one's own movement within an environment and usually includes vestibular, proprioceptive and efferent motor information (e.g., Frissen *et al.*, 2011; Iosa *et al.*, 2012; Waller *et al.*, 2004). The role of body-based information has been extensively investigated by several studies that revealed that participants who had full body-based information showed a better performance than those that had visual cues only (Lessels and Ruddle, 2005; Ruddle and Lessels, 2009). Thus, it seems that body-based information helps people to keep track of the explored location; in particular podokinetic cues seem to be responsible for the learning of the environmental layout and consequently for spatial exploration (Chrastil and Warren, 2013), resulting this to be the primary component of active survey learning.

The importance of body-based information has been established also in the domain of verbally described environments. The tight connection between linguistically provided information and cues deriving from body motion has been widely debated (e.g., Avraamides *et al.*, 2013; Zwaan, 2004), suggesting that physical movement might have a critical role in fostering the development of a spatial representation from verbal information (Giudice *et al.*, 2010). Moreover, it has been demonstrated that full body-based information obtained by walking is effective both for enhancing spatial updating within spatial descriptions (Santoro *et al.*, 2017a) and for reducing the bias for the encoding perspective (Santoro *et al.*, 2017b).

Spatial descriptions provide information about the locations of landmarks and their spatial relation by means of a linguistic text in which such information is contained. The ability to form adequate spatial representations from the verbal descriptions of an environment is supported by empirical evidence (e.g., Giudice *et al.*, 2007). Indeed, it has been demonstrated that people construct spatial mental models containing information regarding described spatial relations even when spatial information is not explicitly described in the text (Bestgen and Dupont, 2003; Rinck *et al.*, 1996). The evidence about people's abilities to construct spatial representations from complex descriptions of unknown spatial configurations (Noordzij and Postma, 2005) has been further strengthened by the outcomes that the representations constructed by the participants exhibited spatial features that reflected the features of the described environment — and not the features of the text itself (Noordzij *et al.*, 2006).

Moreover, it has been demonstrated that a spatial representation built from a verbal description is not only adequate, but functionally equivalent to the spatial representation derived from a visual experience (e.g., Loomis *et al.*, 2002). Several researchers investigated whether such models preserve metric information, demonstrating that the spatial mental models constructed from verbal descriptions are actually similar to perceptual-based mental images, since they preserve the metric information, achieving structural coherence (Denis and Cocude, 1992; Denis *et al.*, 1995). Thus, a spatial representation built from a verbal description maintains a structural coherence with a perceptual-based representation (Afonso *et al.*, 2010).

In summary, previous evidence indicates that physical movement and spatial descriptions are two factors that provide important spatial information. On the one hand, physical movement seems to be an important source of information for building an adequate spatial representation of an environment (Lafon *et al.*, 2009; Picinali *et al.*, 2014). On the other hand, other empirical evidence indicates that spatial descriptions guide the construction of effective spatial mental models (e.g., Bestgen and Dupont, 2003; Cocude *et al.*, 1999; Denis *et al.*, 1995). Unfortunately, each factor presents some limitations that could reduce its effectiveness in supporting spatial representation and navigation. Indeed, it has been suggested that physical navigation impairs spatial memory because of the *mobility monitoring demand*, that is the attentional demand required to walk safely within an environment (Rand *et al.*, 2015); whereas some authors postulated that the increased cognitive load due to the verbal encoding of spatial information negatively affects spatial reasoning (Klatzky *et al.*, 2006).

Since the evidence found in spatial literature is still controversial, the aim of the present study is to examine how the modality with which people encode an environment in the absence of vision influences human spatial navigation within room-size environments; in particular, we compared the effectiveness of physical exploration and spatial descriptions in supporting the physical navigation within an environment.

2. Experiment 1

In Experiment 1 we tested blindfolded sighted participants in order to better understand the role of cues (other than the visual ones) providing spatial information, aiming at examining whether the encoding through spatial description and physical movements differently affects spatial navigation, within a real room-size environment.

According to the evidence previously discussed, we could expect two main scenarios. On the one hand, we could hypothesize better performances for participants who encode the environment through physical movement than for those who encode it through a spatial description, due to the beneficial contribution of body-based information, which mainly involves the egocentric perspective (physical movement hypothesis). Alternatively, we could expect better performances when encoding the environment through spatial description than through physical movement; this scenario may be due to the effectiveness of spatial description, which mainly provides allocentric information (spatial-description hypothesis).

2.1. Method

2.1.1. Participants

Forty university students ($M = 10$; $F = 30$) were recruited for this experiment in exchange for academic credits. Their age varied between 18 and 27 years ($M = 19.8$; SD = 1.4). All participants signed their informed consent before starting the experiment. Participants were naive as to the purpose of the experiment.

2.1.2. Material and Apparatus

The experiment took place in a square area (4 × 4 meters), delimited by wooden panels. This area represented a fictitious room that had to be encoded by participants. The floor of the area was marked by a colored grid to monitor participants' position during the experiment; in particular, the position of seven fictitious objects was marked by 50 × 50 cm squares, as reproduced in Fig. 1. Moreover, a video camera was employed to record the experiment.

2.1.3. Experimental Design

We employed an experimental design with two independent variables, namely, the Encoding modality and the Object position. The Encoding modality variable was manipulated between subjects and refers to the modality through which participants encoded the environment. In this regard, participants were randomly assigned to one of two conditions: Description or Walking. In the Description condition, participants were asked to listen to the description of a fictitious room standing still at the entrance, whereas in the Walking condition participants were asked to walk in a clockwise direction in order to explore the

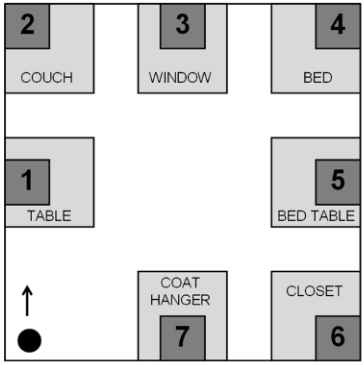

Figure 1. Graphical representation of the environment described. The black dot represents the starting point (and the initial position of the participants); the dark grey areas represent the object locations (two points); the light grey areas represent the object surroundings (one point).

fictitious room. Instead, the Object position variable refers to each location to be encoded in the environment.

2.1.4. Procedure

The experiment included a learning phase, during which participants encoded the fictitious room, and a testing phase during which participants performed a free navigation task.

Learning Phase. The participants were blindfolded at the entrance of the building in which the experiment took place and then they were accompanied into the experimental area. They were positioned at the starting point (i.e., the entrance), which was located at the lower-left corner of the room (see Fig. 1). First of all, participants were informed about the task, namely, mentally representing an environment in order to navigate in it and reach specific locations, corresponding to the objects. Participants were provided with a brief introduction (around 20 s) about the environment concerning a general description of the room (shape and size) and of the objects (number and location): *"You are at the entrance of a 4 × 4 meters room. The entrance is at the lower-left corner of the room. Inside the room there are seven objects: three in the other three corners of the room, the remaining four in the middle of the four walls."* The participants were reassured that they would find no object inside the room, but they were asked to imagine the objects as being actually present in the room. The introduction was the same for both groups of participants, but the encoding of the objects differed for the two conditions.

The participants assigned to the Description condition were provided with a spatial description that explicitly illustrated the location of the objects inside the room and corresponding metric information. When listening to the description, the participants stood still at the entrance. The objects were presented referring to the participants' own position, in a clockwise direction, specifying whether the objects were located in the middle of the wall or in the corner. Thus, referring to Fig. 1, participants were introduced to the first object, located in the middle of the wall on their left (table).Then they were introduced to the second object, located in the corner (couch), and so on. In particular, this is the text of the description (whose duration was about 50 s) verbally provided to participants:

> *"You are standing at the entrance. In the middle of the wall immediately on your left, there is a table, and then in the upper-left corner there is a couch. Then, following the perimeter of the room in a clockwise direction, in the middle of the next wall there is a window, and then at the upper-right corner there is the bed. Then, in the middle of the wall on your right there is a bed table, and then in the lower-right corner there is a closet. Finally, in the middle of the wall with the entrance, there is a coat hanger."*

The participants assigned to the Walking condition were not provided with the spatial description. Instead, they were asked to explore the room, starting from the entrance, by walking around the perimeter in a clockwise direction, accompanied by an experimenter. As soon as they arrived at the fictitious location of an object, the experimenter informed them they had reached the position of that specific object (e.g., "*you have reached the table*"). The exploration ended when participants returned to the starting point. The exploration of the environment took about the same time (around 50 s) as for the Description condition.

Testing Phase. The testing phase was the same for all participants. They were asked to perform a free navigation task while still blindfolded, requiring them to physically reach a specific position inside the room, starting always from the same point (i.e., the entrance). It is important to highlight that the participants were encouraged to take the path they preferred to reach the target, independently from the path walked or the description provided in the encoding phase. In particular, participants were required to perform seven trials; each trial consisted in reaching the location of a different object previously encoded. At the end of each trial the experimenter accompanied the participants back to the starting point.

We measured both the time required to reach the object location and the accuracy of the performance. As regards the latter dependent variable, by looking at the grid on the floor, we assigned two points to trials in which participants stopped at the precise location of the object, and one point when they stopped in the surrounding area (colored in dark and light grey respectively, in Fig. 1). As regards the response times, we measured the time between the end of the trial request (i.e., "*reach object X*") and the moment at which participants declared they had reached the object. These data were extracted from the recordings performed during the experiment.

2.2. Data Analysis and Results

We calculated the average accuracy values and response times for each object in the Walking and Description conditions. As for the response times, only the trials scoring 1 or 2 in terms of accuracy were included in the analysis.

As for the accuracy scores (Fig. 2a), a 2 × 7 (Encoding × Object) mixed-measures ANOVA was performed, revealing a significant main effect for Encoding [$F(1, 38) = 13.861$; $p < 0.001$; $\eta_p^2 = 0.267$], and for Object [$F(6, 228) = 3.944$; $p < 0.005$; $\eta_p^2 = 0.094$]; no significant interaction was found. The average accuracy score in the Walking condition ($M = 1.66$;

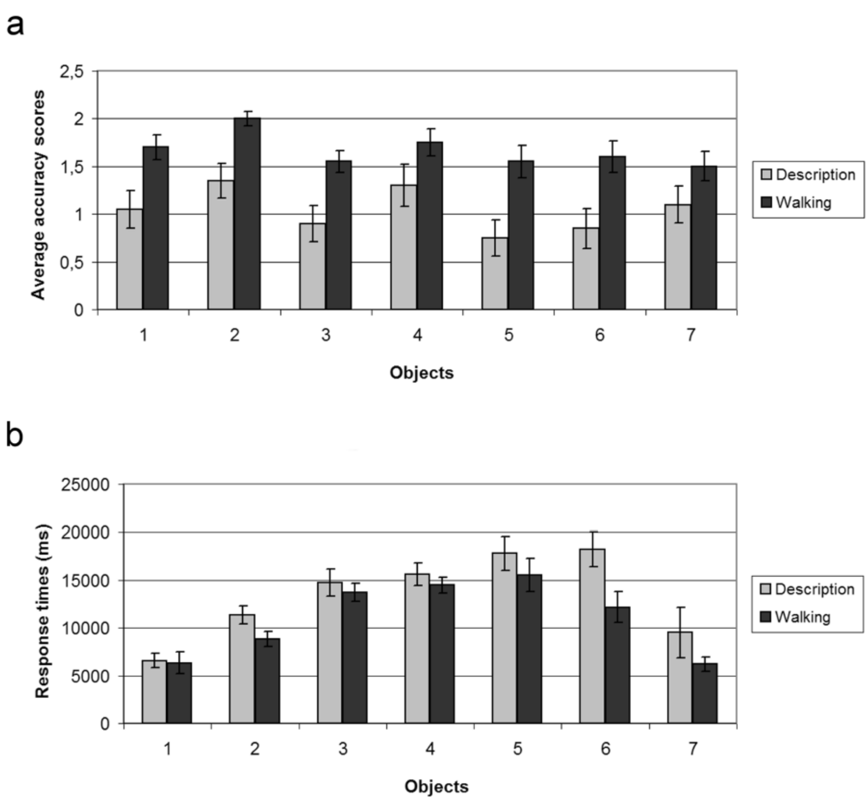

Figure 2. The distribution of (a) the accuracy scores across the object position for each Encoding condition; (b) response times across the object position for each Encoding condition. Bars show standard errors.

SD = 0.61) was significantly higher than that of the Description condition ($M = 1.04$; SD = 0.88).

Similarly, a 2 × 7 (Encoding × Object) mixed-measures ANOVA was performed for response times (Fig. 2b). In this case the results revealed only a significant main effect of Object, [$F(6, 132) = 16.692$; $p < 0.001$; $\eta_p^2 = 0.431$], while neither a significant main effect for Encoding was found, nor the interaction. The average response times in the Walking condition ($M = 11037$ ms; SD = 4972 ms) did not significantly differ from those of the Description condition ($M = 13412$ ms; SD = 6754 ms).

2.3. Discussion

In the present experiment, we investigated the effects of encoding through spatial description and physical movement on spatial navigation within a real room-sized environment; the aim was to compare the effects of the two encoding modalities that in previous research were investigated only separately (e.g., Chrastil and Warren, 2013; Giudice *et al.*, 2010). We expected two main scenarios, as a function of the encoding modality. According to the first scenario (physical movement hypothesis), we hypothesized the superiority of the physical exploration over the spatial description in the navigation task, whereas the second scenario (spatial-description hypothesis) postulated the opposite situation, with the superiority of the spatial description over the physical movement. Results seem to support the physical movement hypothesis.

The results on accuracy scores revealed a significantly better performance for the participants who encoded the room through physical movement, compared to those who encoded it through spatial description. Therefore, it seems that the active exploration of an environment during encoding is an effective modality for spatial navigation within the same environment (e.g., Ruddle and Lessels, 2009). Conversely, the mere verbal description of an environment does not seem equally effective in the same task.

Another result revealed by the analyses on accuracy scores is the significant main effect for the position of the objects. We analyzed the scores obtained for each object, since we wanted to examine whether the location of each object within the room could affect navigation performance differently, depending on the Encoding conditions. However, no significant interaction emerged, suggesting that the performance for participants in the Encoding conditions is not influenced by the position of the target. Indeed, looking at Fig. 2a, it appears that the difference between the participants who encoded the room by walking and through the description is quite stable across all target positions.

As regards response times, an apparent difference between the encoding conditions seems to emerge for each object in Fig. 2b. Statistical analyses revealed that participants who encoded the room by walking were equally fast in reaching the target objects as those who encoded it through the description, however. Conversely, a significant main effect for the object position emerged, suggesting that some objects were reached faster than others. However, it is legitimate to assume that the time needed to reach an object depended on its position: objects closer to the starting point were reached faster than those more distant. Moreover, the analyses of response times revealed no significant interaction, indicating that the average response times did not change across the encoding conditions.

The lack of statistical significance of the encoding modality for response times could be due to the specific characteristics of the experimental procedures, such as the size of the room or the location of the objects. Differently from previous studies, in which wide environmental spaces were used (e.g., Lessels and Ruddle, 2005; Waller and Greenauer, 2007), in our setting the furthest object was 5.6 meters away from the starting point; thus it is possible that the lack of effects for response times was due to the short distances to be walked by our participants. Therefore, future studies should examine whether different results would emerge by manipulating the distances between the targets, and consequently the dimension of the room.

3. Experiment 2

In order to locate objects within the environment and to update their position when moving, usually people rely on sensory modalities different from sight only when vision is not available to them. In Experiment 1 we tested sighted participants that were blindfolded before starting the experimental procedure. Therefore, the participants were exposed to an unfamiliar situation, since they do not usually experience an environment by means of verbal descriptions or physical exploration alone. Several studies investigated the effects of limited vision (such as restricted peripheral field of view) on spatial navigation (Barhorst-Cates *et al.*, 2016; Fortenbaugh *et al.*, 2008), suggesting that the additional attentional resources involved during navigation could somehow negatively affect spatial learning (e.g., Rand *et al.*, 2015).

However, the previous studies manly employed sighted participants, who were not familiar with such sight deprivation, requiring therefore the use of considerable attentional resources. People with visual disabilities, instead, daily experience vision deprivation and it is possible that they face such situations without allocating the additional resources needed for sighted participants. Thus, in Experiment 2 we aimed at investigating whether a pattern of results similar to that found in Experiment 1 would emerge also when testing blind people. In light of the results of Experiment 1, we hypothesized better performances when participants encoded the environment through physical movement than when they encoded it through spatial description (i.e., consistently with the physical movement hypothesis).

3.1. Method

3.1.1. Participants

Nine participants ($M = 5$; $F = 4$) were recruited for this experiment. Their age varied between 30 and 50 years ($M = 42.2$; SD = 5.8). The onset of the blindness occurred when they were between 5 and 47 years old ($M = 18.3$; SD = 14.3). They had been blind for a number of years ranging from 3 to 40 ($M = 23.9$; SD = 13.5). The inclusion criteria were: (1) a diagnosis of late blindness; (2) the absence of cognitive and motor impairments; in particular, regarding the latter point, they had to be able to autonomously walk within a new environment. All participants habitually moved autonomously with a cane. All of them signed the informed consent before starting the experiment. Participants were naive as to the purpose of the experiment.

3.1.2. Experimental Design and Procedure

In Experiment 2, the same experimental design and procedure as in Experiment 1 were employed.

3.2. Data Analysis and Results

In light of the limited number of participants, we performed an explorative analysis in order to obtain some initial information regarding the influence of the two encoding modalities on the spatial navigation of late-blind people. We considered only the frequency distribution of the accuracy scores (2, 1 or 0 points) for each trial obtained in each Encoding condition ($n = 63$).

We applied a chi-squared test, to examine differences between the observed frequencies of the accuracy scores in the two encoding modalities. The analysis revealed that the frequencies of the accuracy scores are differently distributed across the two encoding modalities ($\chi^2 = 24.81$; $p < 0.001$), with higher accuracy in the Walking condition (see Table 1).

3.3. Discussion

In Experiment 2 we aimed to investigate the effects of the encoding modalities, namely, spatial description and physical movements, on spatial navigation

Table 1.
Frequency distribution of accuracy scores across the Description and Walking conditions

Condition	2 points	1 point	0 points	Total
Description	4	6	18	28
Walking	24	8	3	35
Total	28	14	21	63

within a real room-sized environment in a sample of late-blind participants, in order to examine whether a similar pattern of results to that obtained for blindfolded sighted participants would emerge. Consistently with Experiment 1, we hypothesized a better performance in the trials in which participants had physically explored the room, compared to the trials in which participants had listened to the description.

The results seem to confirm our expectation. Indeed, the observation of the frequency distribution of the accuracy scores (2, 1 or 0 points) in the two encoding modalities suggests that the highest accuracy score (2 points) was obtained more frequently in the trials in which the environment was encoded through physical exploration than in the trials in which the environment was encoded through spatial description. Thus, the present data suggest that physical exploration is an effective strategy to encode an environment and navigate in it, also for late-blind people.

An undeniable limitation of the present experiment is the small number of late-blind participants, due to the difficulties in finding and engaging people with this visual impairment, which are at the same time able to autonomously walk within a new environment and without cognitive deficits. However, even with this limitation, the results obtained from such an explorative study are coherent with those found in Experiment 1. Surely, in future studies the sample size should be increased, by involving a higher number of late-blind participants. Indeed, by increasing the sample size, it would be possible to perform the same analysis run in Experiment 1 and compare the results obtained with those of blindfolded sighted participants. However, in the present experiment we wanted to perform a first explorative investigation, in order to get some observations and suggestions for the future development of dedicated research. Moreover, in future studies it will be interesting to include also early-blind participants — people who had no previous experience of sight or no memory of it — to evaluate how they would perform in a similar experimental situation, thus considering the influence of past visual experiences on spatial encoding and navigation strategies.

It is noteworthy that in the present experiment, we involved only late-blind participants, that is, people who became blind during their life and, therefore, had previous visual experiences. For this reason, it is possible that the visual experiences gained by our participants in their past have affected the strategies they used to encode a new environment and move within it; thus, the strategies acquired through past visual experiences could still be used even without the support of visual cues. In other words, they might have used the same modality of encoding the environment as sighted people (e.g., Iachini and Giusberti, 2004; Iachini and Ruggiero, 2010; Ruotolo *et al.*, 2012). Further investigation is necessary to better clarify this possible explanation.

4. General Discussion

The aim of the present study was to investigate the influence of two encoding modalities — that is, spatial description and physical movement — on a spatial navigation task within a room-sized environment. In particular, in two experiments we examined the effectiveness of these encoding modalities by involving both blindfolded sighted and late-blind participants.

In both experiments, we found evidence suggesting that encoding a room-sized environment through physical exploration determines better performances as for accuracy scores than encoding the same environment through verbal descriptions, in a spatial navigation task (consistent with our physical-exploration hypothesis). Our outcomes suggest that the body-based information obtained through physical exploration within an environment supports spatial learning and navigation more effectively than spatial description. Thus, our findings are in line with studies claiming that the physical exploration of an environment enhances the development of a global spatial representation and improves spatial updating (Santoro *et al.*, 2017a, b).

Unfortunately, we did not find any significant effect of the encoding modalities on the response times, suggesting that the time required to reach each target object might be more influenced by the navigation strategies (for example, walking in a clockwise or counterclockwise direction along the walls, or walking towards the center of the room and then reorienting) than by the previous encoding modality. Moreover, the lack of effect on the response times can be due to the dimensions of the considered environment, as already discussed in Experiment 1. However, the response times provide us with important indications regarding the strategies used by participants and, in particular, on the route they followed (the longer the route, the longer the response times). Indeed, one potential criticism of the present work regards the strategies adopted by participants in the navigation task, based on the encoding modality. In this regard, it could be argued that the different accuracy results might be explained in terms of congruency between encoding and testing modalities, as walking during encoding requires physical movement as well as the navigation task, and participants could have simply re-enacted the same motor schemes. However, if participants simply re-enacted the motor schemes, the response times should have linearly increased from object 1 to object 7. As a matter of fact, observing Fig. 2b, it appears quite evident that in the Walking condition there is not a linear trend. Rather, the time spent by participants to reach the objects 6 and 7 tends to decrease, compared to that spent for the objects 3, 4 and 5 (the physically farthest ones). This indicates that the strategy used by the majority of participants to reach the two objects, which were physically close but ‘encodingly’ far (objects 6 and 7), was to navigate in a counterclockwise direction, namely, the way opposite to that of the exploration. This suggests that they created and used a spatial representation of the environment, rather than simply re-enacting the motor schemes of the exploration. Interestingly, the average accuracy scores in all trials are always between 1.5 and 2, and appear relatively independent from the route followed by participants. It is noteworthy that in the Description condition the participants seem more bound to the order of the objects presented in the description, given that the response times linearly increase up to object 6 and decrease only for object 7 (for which the strategy switch occurred).

As for the mechanisms underpinning our outcomes, the different results yielded by the two encoding modalities can be explained in terms of information encoding, representation and retrieval (i.e., navigation). Indeed, it is possible that body-based information obtained by walking enhances the encoding of the environment and consequently its spatial representation, thus leading to higher accuracy scores in the navigation task (Ruddle and Lessels, 2009). Alternatively, it is possible that the observed results reflect the difficulty for participants in the spatial-description condition to translate allocentric into egocentric information. Indeed, while it is reasonable that the participants of the physical-exploration condition represented the room from an egocentric perspective, we cannot be sure about how the participants of the spatial-description condition represented it. On the one hand, it is possible that participants used the verbal information to represent the room from an egocentric perspective (e.g., imagining themselves walking in the room while listening to the description). On the other hand, it is possible that participants used the allocentric information embedded in the spatial description to create an allocentric representation of the room (e.g., 'watching' the room from an external point of view). Given that to perform the navigation task effectively participants needed to assume an egocentric perspective, if the majority of participants of the spatial-description condition created an allocentric representation of the room, then it is possible that their poorer performances were due to the aforementioned difficulty to switch from an allocentric to an egocentric representation during the navigation task. As a matter of fact, we do not have any proof about the perspective (either allocentric or egocentric) used by participants to represent the room; this aspect should be further investigated, for instance manipulating the instructions to foster one of the two kinds of perspectives. More generally, the two environment encoding modalities manipulated in our study (physical exploration and spatial description) may elicit differences at a level more basal than navigation, namely, either at the encoding or at the representational level. Future studies should examine whether both environment encoding and representation are affected by the encoding modality, or the differences are attributable only to one of these two levels.

From an applied perspective, our results provide interesting suggestions concerning how people learn a new room-sized environment when sight-deprived. When visually impaired people have to learn the layout of a room (for example, a hotel room), in order to successfully navigate within it, they usually encode the information by listening to verbal descriptions that are provided by a sighted observer. This learning strategy seems to have undeniable 'technical' advantages, such as the possibility to listen to the description off-line before experiencing the environment, or to communicate the same information to several individuals at the same time. However, our results suggest that encoding the environment through physical movement is more effective in supporting active navigation than verbal descriptions. Even though further studies are necessary to confirm the occurrence of similar results by testing a higher number of people with different visual impairments, if confirmed, these results could improve the experience of visually impaired people within a new environment by allowing them to explore it.

In conclusion, while previous studies investigated the effects of physical movement (e.g., Chrastil and Warren, 2013) and verbal descriptions (e.g., Giudice *et al.*, 2010) separately, in the present study we compared them. We demonstrated that, for spatial navigation, learning a real room-size environment by actively walking is more effective than the mere verbal description of the environment itself. Our results are in line with previous studies that indicate the importance of physical movement to guide spatial navigation and to support the development of spatial abilities (e.g., Schmidt *et al.*, 2013; Ungar *et al.*, 1996). In our opinion, body-based cues obtained during walking play a crucial role in fostering spatial navigation within a room-sized environment, and the beneficial effects of these cues should lead to a stronger consideration of physical movement as an effective environmental learning strategy.

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References

Afonso, A., Blum, A., Katz, B. F. G., Tarroux, P., Borst, G. and Denis, M. (2010). Structural properties of spatial representations in blind people: scanning images constructed from haptic exploration or from locomotion in a 3-D audio virtual environment, *Mem. Cogn.* **38**, 591–604.

Avraamides, M. N., Galati, A., Pazzaglia, F., Meneghetti, C. and Denis, M. (2013). Encoding and updating spatial information presented in narratives, *Q. J. Exp. Psychol.* **66**, 642–670.

Barhorst-Cates, E. M., Rand, K. M. and Creem-Regehr, S. H. (2016). The effects of restricted peripheral field-of-view on spatial learning while navigating, *PloS One* **11**, e0163785. DOI:10.1371/journal.pone.0163785.

Bestgen, Y. and Dupont, V. (2003). The construction of spatial situation models during reading, *Psychol. Res.* **67**, 209–218.

Chrastil, E. R. and Warren, W. H. (2013). Active and passive spatial learning in human navigation: acquisition of survey knowledge, *J. Exp. Psychol. Learn. Mem. Cogn.* **39**, 1520–1537.

Cocude, M., Mellet, E. and Denis, M. (1999). Visual and mental exploration of visuo-spatial configurations: behavioral and neuroimaging approaches, *Psychol. Res.* **62**, 93–106.

Denis, M. and Cocude, M. (1992). Structural properties of visual images constructed from poorly or well-structured verbal descriptions, *Mem. Cogn.* **20**, 497–506.

Denis, M., Goncalves, M.-R. and Memmi, D. (1995). Mental scanning of visual images generated from verbal descriptions: towards a model of image accuracy, *Neuropsychologia* **33**, 1511–1530.

Fortenbaugh, F. C., Hicks, J. C. and Turano, K. A. (2008). The effect of peripheral visual field loss on representations of space: evidence for distortion and adaptation, *Invest. Ophthalmol. Vis. Sci.* **49**, 2765–2772.

Frissen, I., Campos, J. L., Souman, J. L. and Ernst, M. O. (2011). Integration of vestibular and proprioceptive signals for spatial updating, *Exp. Brain Res.* **212**, 163–176.

Giudice, N. A., Bakdash, J. Z. and Legge, G. E. (2007). Wayfinding with words: spatial learning and navigation using dynamically updated verbal descriptions, *Psychol. Res.* **71**, 347–358.

Giudice, N. A., Bakdash, J. Z., Legge, G. E. and Roy, R. (2010). Spatial learning and navigation using a virtual verbal display, *ACM Trans. Appl. Percept.* **7**, 3. DOI:10.1145/1658349.1658352.

Iachini, T. and Giusberti, F. (2004). Metric properties of spatial images generated from locomotion: the effect of absolute size on mental scanning, *Eur. J. Cogn. Psychol.* **16**, 573–596.

Iachini, T. and Ruggiero, G. (2010). The role of visual experience in mental scanning of actual pathways: evidence from blind and sighted people, *Perception* **39**, 953–969.

Iosa, M., Fusco, A., Morone, G. and Paolucci, S. (2012). Walking there: environmental influence on walking-distance estimation, *Behav. Brain Res.* **226**, 124–132.

Jürgens, R. and Becker, W. (2006). Perception of angular displacement without landmarks: evidence for Bayesian fusion of vestibular, optokinetic, podokinesthetic, and cognitive information, *Exp. Brain Res.* **174**, 528–543.

Klatzky, R. L., Marston, J. R., Giudice, N. A., Golledge, R. G. and Loomis, J. M. (2006). Cognitive load of navigating without vision when guided by virtual sound versus spatial language, *J. Exp. Psychol. Appl.* **12**, 223–232.

Lafon, M., Vidal, M. and Berthoz, A. (2009). Selective influence of prior allocentric knowledge on the kinesthetic learning of a path, *Exp. Brain Res.* **194**, 541–552.

Lessels, S. and Ruddle, R. A. (2005). Movement around real and virtual cluttered environments, *Presence (Camb.)* **14**, 580–596.

Loomis, J. M., Lippa, Y., Klatzky, R. L. and Golledge, R. G. (2002). Spatial updating of locations specified by 3-D sound and spatial language, *J. Exp. Psychol. Learn. Mem. Cogn.* **28**, 335–345.

Noordzij, M. L. and Postma, A. (2005). Categorical and metric distance information in mental representations derived from route and survey descriptions, *Psychol. Res.* **69**, 221–232.

Noordzij, M. L., Zuidhoek, S. and 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.

Picinali, L., Afonso, A., Denis, M. and Katz, B. F. G. (2014). Exploration of architectural spaces by blind people using auditory virtual reality for the construction of spatial knowledge, *Int. J. Hum. Comput. Stud.* **72**, 393–407.

Rand, K. M., Creem-Regehr, S. H. and Thompson, W. B. (2015). Spatial learning while navigating with severely degraded viewing: the role of attention and mobility monitoring, *J. Exp. Psychol. Hum. Percept. Perform.* **41**(3), 649–664.

Rinck, M., Williams, P., Bower, G. H. and Becker, E. S. (1996). Spatial situation models and narrative understanding: some generalizations and extensions, *Discourse Process.* **21**, 23–55.

Ruddle, R. A. and Lessels, S. (2009). The benefits of using a walking interface to navigate virtual environments, *ACM Trans. Comput. Hum. Interact.* **16**, 5. DOI:10.1145/1502800.1502805.

Ruotolo, F., Ruggiero, G., Vinciguerra, M. and Iachini, T. (2012). Sequential vs simultaneous encoding of spatial information: a comparison between the blind and the sighted, *Acta Psychol.* **139**, 382–389.

Santoro, I., Murgia, M., Sors, F. and Agostini, T. (2017a). Walking reduces the gap between encoding and sensorimotor alignment effects in spatial updating of described environments, *Q. J. Exp. Psychol.* **70**, 750–760.

Santoro, I., Murgia, M., Sors, F., Prpic, V. and Agostini, T. (2017b). Walking during the encoding of described environments enhances a heading-independent spatial representation, *Acta Psychol.* **180**, 16–22.

Schmidt, S., Tinti, C., Fantino, M., Mammarella, I. C. and Cornoldi, C. (2013). Spatial representations in blind people: the role of strategies and mobility skills, *Acta Psychol.* **142**, 43–50.

Ungar, S., Blades, M. and Spencer, S. (1996). The construction of cognitive maps by children with visual impairments, in: *The Construction of Cognitive Maps*, J. Portugali (Ed.), pp. 247–273. Kluwer Academic Publishers, Dordrecht, Netherlands.

Waller, D. and Greenauer, N. (2007). The role of body-based sensory information in the acquisition of enduring spatial representations, *Psychol. Res.* **71**, 322–332.

Waller, D., Loomis, J. M. and Haun, D. B. M. (2004). Body-based senses enhance knowledge of directions in large-scale environments, *Psychon. Bull. Rev.* **11**, 157–163.

Zwaan, R. A. (2004). The immersed experiencer: toward an embodied theory of language comprehension, in: *The Psychology of Learning and Motivation, Vol. 44*, B. H. Ross (Ed.), pp. 35–62. Academic Press, Amsterdam, Netherlands.