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Structural properties of spatial representations in blind people: Scanning images constructed from haptic exploration or from locomotion in a 3-D audio virtual environment

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When people scan mental images, their response times increase linearly with increases in the distance to be scanned, which is generally taken as reflecting the fact that their internal representations incorporate the metric properties of the corresponding objects. In view of this finding, we investigated the structural properties of spatial mental images created from nonvisual sources in three groups (blindfolded sighted, late blind, and congenitally blind). In Experiment 1, blindfolded sighted and late blind participants created metrically accurate spatial representations of a small-scale spatial configuration under both verbal and haptic learning conditions. In Experiment 2, late and congenitally blind participants generated accurate spatial mental images after both verbal and locomotor learning of a full-scale navigable space (created by an immersive audio virtual reality system), whereas blindfolded sighted participants were selectively impaired in their ability to generate precise spatial representations from locomotor experience. These results attest that in the context of a permanent lack of sight, encoding spatial information on the basis of the most reliable currently functional system (the sensorimotor system) is crucial for building a metrically accurate representation of a spatial environment. The results also highlight the potential of spatialized audio-rendering technology for exploring the spatial representations of visually impaired participants.

The research reported here was intended to account for the properties of mental representations of spatial information, when these representations are constructed from nonvisual sensory modalities. We therefore compared representations constructed by sighted and blind people. By doing this, we connected two fields of research—namely, mental imagery and blindness. The connection between these two fields has been amply documented (e.g., Cornoldi & Vecchi, 2000; De Beni & Cornoldi, 1988; Ernest, 1987; Kaski, 2002; Marmor & Zaback, 1976; Zimler & Keenan, 1983). Here, we extended this effort of connecting the two fields of research by using a method that seemed likely to provide a useful new perspective on this domain—namely, the image-scanning paradigm.

Image scanning is conceived of as the systematic shifting of attention across visualized patterns—for instance, in the context of a task in which a person tries to check for the presence of an object in a scene or of a specific detail within an object (see Denis & Kosslyn, 1999; Kosslyn, Thompson, & Ganis, 2006). The main finding from image-scanning studies has been that when people mentally scan the image of an object or a scene, their scanning time increases linearly as the scanned distance increases (e.g., Beech, 1979; Borst & Kosslyn, 2008; Borst, Kosslyn, & Denis, 2006; Dror, Kosslyn, & Waag, 1993; Kosslyn, Ball, & Reiser, 1978; Pinker, Choate, & Finke, 1984). This correlational pattern is generally taken to reflect the structural isomorphism between a visuospatial representation and the spatial layout from which the representation has been constructed. Thus, spatial mental images preserve the relative metric properties of the layout.[1]

A critical issue here is to determine the extent to which the properties of images—in particular, their capacity of preserving the metric properties of the objects that they evoke—depend on their visuospatial substrate. The images constructed from visual experience have been shown

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to possess an internal structure that displays the metric relationships between the parts of the corresponding objects or scenes. However, does the analogical nature of such representations essentially depend on their visuospatial nature? This is a pertinent question because most of the experiments that have been conducted on this topic so far have used visual information as an input for the creation of visual images. We therefore wanted to find out whether the acquisition of spatial information mediated by nonvisual modalities—in particular, by visually impaired or blind people—results in internal representations that have the same properties. If such properties were not found, the isomorphism should be considered to be intrinsically dependent on the visuospatial nature of images. On the other hand, if these properties were found, the isomorphism of the representations should be considered as a more general property, not uniquely dependent on visual experience.

The image-scanning paradigm was originally developed in the context of research on visual mental imagery but can be extended to other sensory modalities. Thus, by applying the paradigm to the investigation of spatial representations formed by blind people, we intended to test the hypothesis that spatial representations created without visual experience contain accurate metric information about learned configurations or environments. Of course, there is no doubt that blind people master a number of space-related tasks—in particular, locomotion—which is indicative of the fact that they do, indeed, acquire spatial information via nonvisual modalities (e.g., Millar, 1994). However, although there is a considerable body of data reflecting the capacity of blind people to create and use spatial memories, we wanted to find out more about the *representations* on which their space-related behavior is based. In particular, do these representations include a metric that gives them the status of analogue representations (like the visuospatial representations constructed from the visual experience of configurations or environments)? Very little is known about this, and the sparse data available do not offer an integrated view of the situation. We therefore set out to obtain a more systematic assessment of whether spatial representations derived from different modalities exhibit similar properties and to determine whether proficiency in spatial learning via a particular modality depends on the amount of previous visual experience in life (i.e., by comparing sighted, late blind, and congenitally blind people).

Haptic Exploration

Some of the research into whether spatial representations created from nonvisual sensory modalities display the same structural properties as those created from the visual modality has used the image-scanning paradigm to document these properties. Two studies have involved blind participants in image-scanning tasks in which spatial configurations were learned via the haptic modality. The first was a study by Kerr (1983), in which 10 congenitally blind participants performed tactile exploration of a board to which seven raised figures were affixed. When invited later to scan mentally across the board from the location of one figure to that of another one, the participants' scanning times increased linearly with increasing distances, indicating that the mental representation constructed from haptic learning did include accurate metric information. Kerr also found that blind people tended to take longer than their sighted counterparts who had learned the same configuration by visual inspection. This finding suggested that the structure of mental representations of spatial configurations can be achieved despite the absence of sight, although the cost of generating and scanning these representations is higher for blind people.

In a further study, Röder and Rösler (1998) subjected sighted participants to visual, haptic, or visual and haptic learning of a spatial configuration containing five objects. All three learning conditions resulted in similar scanning performance when the participants were later asked to move mentally between pairs of objects. In addition, when congenitally blind participants were involved in haptic learning of the configuration, their data displayed the same linear relationship between scanning times and distances as those from the (blindfolded) sighted people, but in contrast to Kerr's (1983) study, the absolute scanning times were not significantly different between the sighted and the blind people.

Beyond the problem of the disparity between the outcomes of these two studies, neither was entirely free of methodological problems. In particular, in Kerr's (1983) study, although all 10 participants were described as having been blind from birth, only 4 of them were said to be "totally blind," and the other 6 had at least minimal light perception or were able to see contrast. In order to avoid similar problems, stricter criteria seemed to be called for, and we decided to investigate two separate groups, consisting of early and late blind participants, respectively. Furthermore, the number of participants in Kerr's study may have been rather small. Lastly, the blind participants learned the configuration haptically, whereas the sighted controls learned it visually. This use of different learning procedures limited the comparability of the results for the sighted and the blind participants. In Röder and Rösler's (1998) study, under conditions involving haptic learning, the participants were invited to explore the configuration with both hands without any time limit. It may be appropriate in such experiments to avoid interindividual differences in the learning procedure.

Locomotion

In the absence of sight, locomotor experience is an alternative source of information for constructing mental representations of an environment. There has been a substantial amount of work done to investigate the capacity of blind people to navigate in complex environments without relying on visual input (e.g., Loomis et al., 1993; Millar, 1994; Tinti, Adenzato, Tamietto, & Cornoldi, 2006; Veraart & Wanet-Defalque, 1987). Little is known, however, about the nature and structure of the representations that blind people use to underpin their navigational performance. Once again, image scanning provides a reliable means of assessing the metric properties of mental images and to tell us about the structure of blind people's mental representations of space.

Iachini and Giusberti (2004) investigated several variants of a situation in which sighted participants learned an environment by walking along paths connecting distinctive landmarks. They were then invited to mentally scan distances of various lengths by imagining that they were moving from one landmark to another one. The results showed that scanning time increased with the distance scanned, which suggested that the mental representation of space based on locomotor exploration preserves information about the relative distances separating different locations. In another experiment, Iachini and Giusberti compared two learning conditions, one that involved visually inspecting the pathway (without locomotion), and the other physically walking along the pathway but without seeing it (blindfolded and guided by the experimenter). The scanning task revealed once again that both learning conditions resulted in the same typical time/distance correlation but that absolute scanning times were shorter after the visual than after the locomotor learning condition. This finding is in line with the results of studies showing that sight and visual strategies enhance the speed and accuracy of spatial performance (see Cattaneo, Fastame, Vecchi, & Cornoldi, 2006; Thinus-Blanc & Gaunet, 1997; Vecchi, 1998). However, the same kind of experiment still needs to be conducted with blind participants, in order to clarify whether their mental representations preserve the metric properties of the learned environment. Here, the distinction between congenitally and late blind people is pertinent, since locomotion is, in fact, the only way by which congenitally blind people can apprehend large spaces.

Verbal Descriptions

In addition to the haptic and the locomotor modalities, both of which involve an alternative to sight, some consideration must be given to language as a vehicle of spatial information in the absence of a visual contact of a person with a scene, as much for the sighted as for the blind (see Bloom, Peterson, Nadel, & Garrett, 1996). The image-scanning paradigm offers a particularly useful way of finding out whether the scanning effect (i.e., the linear increase in scanning time with increasing distance) will also be detected after verbal descriptions of spatial configurations are processed in the absence of any prior visual contact with the corresponding visual layout. Several previous studies have reported evidence that spatial mental images constructed from verbal descriptions can indeed preserve metric information and, thus, achieve structural coherence that makes them similar to perception-based spatial images (e.g., Denis & Cocude, 1992; Denis, Gonçalves, & Memmi, 1995).

In a study that involved only sighted people (Mellet et al., 2002), the participants learned survey descriptions of complex spatial environments containing a number of landmarks of which the relative positions were asserted, but without any specification of a metric. Once learning had been completed, the participants were invited to generate a survey image of an environment and to mentally scan between pairs of landmarks. After completing the image-scanning task, the participants were asked to draw maps of the environments. In these maps, the distance between each pair of landmarks was measured. For each participant, the correlation between scanning times and distances was computed. Positive correlation coefficients were obtained, four out of six of which were significant. This provides evidence that people are able to construct mental representations of space in which metric information is accurately encoded.

In a further study, Chabanne, Péruch, Denis, and Thinus-Blanc (2004) compared image-scanning performance following the learning of the verbal description of a spatial configuration in which either a survey or a route perspective was used (i.e., a description of the territory from a bird's eye view or from the successive points of view of a pedestrian navigating the environment). The results showed that scanning times were shorter after survey acquisition than after route acquisition and that they consistently increased as a function of the Euclidean distances between the locations in the environment. Mental spatial representations derived from different perspectives thus preserve the metric characteristics of the original environment, but they are easier for sighted people to access when they have been constructed from a survey perspective.

In a subsequent study using similar learning situations (involving either a route or a survey perspective), Péruch, Chabanne, Nesa, Thinus-Blanc, and Denis (2006) asked participants to assess the metric features of an environment by performing mental comparisons of distances. The frequency of correct responses was higher, and the response times (RTs) were shorter when the participants had learned about the environment from the survey perspective rather than from the route perspective. These findings support the view that representations from sources involving different perspectives contain genuine metric information but that access to this information is more difficult when it has been constructed from a route perspective. With a similar distance comparison task, Noordzij, Zuidhoek, and Postma (2006) showed that blind people were able to form spatial mental models from both route and survey descriptions and that they exhibited the same patterns of chronometric responses as sighted people. Interestingly, in contrast to sighted people, blind people performed better after listening to the route description than after listening to the survey description of the environment.

The rationale of the research reported here was to use image scanning to assess the metric properties of mental images and provide us with information about the structure of the representations constructed by blind people. Apart from the very small number of studies we have already cited (Kerr, 1983; Röder & Rösler, 1998), the potential of the scanning paradigm has yet to be exploited—in particular, in people with sensory impairment. We therefore based our approach on the belief that if mental representations that are not supported by visual experience have structural characteristics and incorporate metric information, these properties should be assessed by the same method as the one that allowed Kosslyn (e.g., Kosslyn et al., 1978) and others to reveal the analogue structure of visual images. In this case, one would expect to find a strong positive correlation between RTs and distances when participants perform the scanning task. The novel feature of this research was that it considered several different learning modalities that can be used efficiently by people with no sight. The objective was to provide a more integrated account of a question for which only disconnected approaches have been used so far.

EXPERIMENT 1

Experiment 1 was intended to account for the representations of a spatial configuration constructed by sighted and blind people in two modalities devoid of visual content. To do this, we measured the scanning times of participants who had learned the configuration either from a verbal description (as in the experiments of Chabanne et al., 2004) or from haptic exploration of that configuration (as in the Röder and Rösler, 1998, study). The two learning conditions (verbal and haptic) were investigated within the same experimental design, using materials common to the two conditions. Furthermore, as is usual in research on the blind, we considered two groups of blind people—namely, one with early-onset and the other with late-onset blindness. They were compared with a matched group of sighted participants.

Method

Participants. The experiment involved 72 participants, with ages ranging from 21 to 63 years. All the participants were autonomous in their daily life, with many activities and hobbies, as assessed from their responses to a questionnaire. They were recruited through two associations of blind people and through personal contacts. One group was composed of 24 congenitally blind people who had been totally blind from birth due to glaucoma, retinitis pigmentosa, malnutrition, or some other unidentified origin. A second group comprised 24 people with late-onset blindness who had lost their sight between the ages of 6 and 30 years due to optic nerve atrophy, congenital cataract, glaucoma, bilateral eye tumor, or an accident. All of these participants had been totally blind for more than 15 years. The third group consisted of 24 sighted people. Each group comprised equal numbers of men and women. In addition to gender, the groups were matched for age, as well as for educational and sociocultural background. Equal numbers of participants in each group were assigned to the two learning conditions.

Materials. The materials used were adapted from those developed by Denis and Cocude (1992). For the verbal condition, the materials used in the learning phase consisted of a short text describing a circular island, around the shore of which six geographical landmarks were located. All of the French names for these landmarks were pronounced as one-syllable words. The locations of the landmarks were defined using the conventional clock-face terms of aerial navigation. The text read as follows (original in French): "The island is circular in shape. Six features are located around its edge. At 11 o'clock, there is a harbor. At 1 o'clock, there is a lighthouse. At 2, there is a creek. Midway between 2 and 3, there is a hut. At 4, there is a beach. At 7, there is a cave."

In the learning phase of the haptic condition, a map of the island was used, which took the form of a metal disk. The disk was 50 cm in diameter and was displayed vertically in front of the participants. Six tags representing the six landmarks were fixed to the edge of the disk at positions corresponding to those specified in the verbal description.

A list of 60 pairs of landmark names was used. Each of the six landmarks was named 10 times and was followed 4 sec later by a second name. On five of these trials, the second name referred to a landmark that was not, in fact, present on the island (*false* trials). These five names referred to objects that could well have been present on the island (meadow, bridge, well, mine, moor). On the other five trials, the first name was followed by the name of one of the other five landmarks present on the island (*true* trials). Thus, each pair of landmarks occurred twice, alternating the landmark mentioned first. The order of the pairs was randomized. The resulting list was used for half of the participants in each condition. For the other half of the participants, the list was split into two halves, and the order of each of the two halves was reversed. The presentation of the second name started a chronometer. Whether the participant had responded or not, a new trial began 8 sec after the probe word had been presented. The test trials were preceded by eight practice trials (four true and four false). The practice trials used the names of French cities as true items. The whole procedure was driven by a computer program adapted to the needs of the experiment.

Procedure. Essentially, the procedure was similar to the one used in image-scanning experiments with perceptual learning (e.g., Kosslyn et al., 1978) or verbal learning (e.g., Denis & Cocude, 1992). A distinct feature of the present experiment was that the participants in the sighted groups were blindfolded throughout the entire experiment.

At the beginning of the learning phase, the participants in the verbal condition were told that they would hear a description of the map of an island, of which they were invited to create as vivid and accurate a mental representation as possible. In order to provide a cue for the size of the configuration to be imagined, the experimenter presented a 50-cm disk to the participants and invited them to explore it haptically for 1 min. After the disk had been removed, the experimenter read aloud the description three times. Following each presentation of the description, the participants were required to review mentally the name of each landmark and its position on the island and then to repeat the description aloud (landmark names and their respective positions). If, after the third presentation of the description, a participant was not able to correctly recall the landmark names and positions, the learning procedure was repeated until the participant provided a correct description of the configuration.

For the haptic condition, the participants were first presented with the metal disk. The disk served as a cue for the size of the configuration to be imagined. The experimenter then positioned six magnets along the edge of the disk at the positions mentioned in the description. In order for the participants to create a mental image of the configuration, the experimenter moved the dominant hand of the participants from magnet to magnet in a clockwise direction, indicating for each one which landmark it referred to. No verbal information was given on the positions of the landmarks (in terms of "hours" on a clock face). When guiding the participant's hand from location to location, the experimenter took care to follow a time schedule as similar as possible to the flow of the successive sentences read in the verbal condition. After each haptic exploration, the magnets were removed, and the participants were invited to put them back and state the name of the landmark at each given position. If a magnet was incorrectly positioned (by more than 1 cm from the correct position), the experimenter directed the participant's hand to where the participant had placed it and then to the correct position. If, at the third reconstruction of the configuration, one of the magnets was still misplaced, the procedure was repeated until the participants' reconstruction was correct. No participant needed more than four trials to reach the learning criterion.

The test phase consisted of the scanning task, which proceeded in the same way for all the participants. The participants were first invited to reconstruct mentally the configuration of the island and to check the positions of the six landmarks. They were then told that each trial would consist first of hearing the name of a landmark on the island. They then would be required to position this item at its correct place in their mental image and focus on it. They were told that a few seconds later, they would hear another word. If this word designated a landmark present on the island, the participants should scan to it by imagining a little spot moving to that landmark along a straight line at a constant rate. They should then press a key with their dominant hand to signal that scanning had been completed. If the second word in a pair did not correspond to any of the landmarks on the map, the participants were to press a different key with their nondominant hand. Their RTs were recorded.

As a final check, after the test phase, the participants in the verbal condition group were invited to recall the verbal description, and those in the haptic condition group were invited to place the magnets on the metal disk again. All the participants provided correct recall or reconstruction of the configuration.

The participants were tested individually. They were interviewed at the end of the experiment. Two participants who reported having followed the instructions less than 75% of the time during the test phase were replaced. The participants in the verbal condition were also asked whether they had relied on the location of the landmark in their mental representation or had first revised the hour-coded location of the landmark before mentally scanning to the second landmark named. One participant who said that he had used the hour-coded location was replaced.

Results

Only the times for the correct true items were included in the analysis. In fact, the error rate was very low (0.7%). Before analyzing the data, we eliminated the outliers, defined as any RTs greater than $M + 2$ *SD*s (or less than $M - 2$ *SD*s) for a given participant. In such cases, the RT was replaced by the average RT $+ 2$ *SD*s (or $- 2$ *SD*s). Outliers occurred on 2.6% of the trials.

For each participant and each distance, we averaged the RTs over trials. The total number of distinct pairs of landmarks was 15, but due to the fact that several pairs were separated by identical distances, we averaged the values collected for the same distances, this resulting in a total of 10 different distances. The time/distance correlation coefficients were thus computed on the basis of 10 values.

We analyzed the RTs in each learning condition separately over the three groups of participants. In order to control for familywise error rate, all p values were corrected using the Bonferroni procedure. For example, given that we conducted four separate ANOVAs to assess the effect of distance on RTs in each learning condition, each p value in each ANOVA was multiplied by 4.

One-way repeated measures ANOVAs revealed a significant effect of distance on RTs in both learning conditions [$F(9,315) = 7.31$, $p < .001$, $\eta^2 = .17$, in the verbal condition, and $F(9,315) = 8.02$, $p < .001$, $\eta^2 = .19$, in the haptic condition]. In both conditions, the best-fitting linear function, calculated by the method of least squares, revealed that times increased linearly with increases in distances [$F(1,35) = 41.65$, $p < .001$, $\eta^2 = .30$, and $F(1,35) = 33.00$, $p < .001$, $\eta^2 = .25$, respectively]. The linear component accounted for 63.3% of the variance of the distance effect for the verbal condition and 47.6% for the haptic condition. In both conditions, the residual variance was significant [$F(8,280) = 3.01$, $p < .025$, $\eta^2 = .08$, for the verbal condition, and $F(8,280) = 4.89$, $p < .001$, $\eta^2 = .12$, for the haptic condition]. However, in both conditions, RTs were significantly correlated with the distances scanned [$r(8) = .89$, $p < .01$, for the verbal condition, and $r(8) = .69$, $p < .05$, for the haptic condition]. The scanning times (averaged over the groups) did not differ significantly for the two conditions ($M = 1{,}551$ and 1,654 msec, respectively; $t < 1$). Using Steiger's (1980) equation based on Fisher's (1921) z transformation, we did not find the correlation coefficients between the scanning times (averaged over participants) and the distances to be significantly different from each other ($z = 1.07$, $p = .14$).

The subsequent analyses were intended to contrast the responses for the two conditions, taking each group separately, focusing particularly on the time/distance correlation within each group and each condition.

Sighted participants. A one-way repeated measures ANOVA revealed that the sighted participants' times varied with distances for both learning conditions [$F(9,99) = 6.87$, $p < .001$, $\eta^2 = .39$, after processing of the verbal description, and $F(9,99) = 4.71$, $p < .001$, $\eta^2 = .30$, after haptic exploration of the configuration]. Times increased linearly with distance [$F(1,11) = 56.56$, $p < .001$, $\eta^2 = .39$, and $F(1,11) = 29.44$, $p < .001$, $\eta^2 = .25$, respectively]. The linear trend accounted for 91.4% of the variance due to the distance between the landmarks in the verbal condition and for 69.5% in the haptic condition. Residual variances were not significant for either condition [$F < 1$ for the verbal condition, and $F(8,88) = 1.61$, $p = .52$, for the haptic condition]. The participants did not require significantly different time to scan their images in the verbal condition ($M = 1{,}433$ msec) and the haptic condition ($M = 1{,}545$ msec) ($t < 1$).

Figure 1A shows the relationship between scanning times and distances for the sighted participants. Time/distance correlation coefficients were computed for each condition. The coefficients were significant for both the verbal and the haptic conditions [$r(8) = .96$, $p < .01$, and $r(8) = .80$, $p < .01$, respectively]. We did not find any significant difference between the coefficients ($z = 1.53$, $p = .06$).

Late blind participants. An ANOVA showed that the effect of distance on scanning times was significant [$F(9,99) = 4.19$, $p < .001$, $\eta^2 = .28$, after the processing of the verbal description, and $F(9,99) = 4.59$, $p < .001$, $\eta^2 = .30$, after haptic exploration], with significant linear effects of distance [$F(1,11) = 24.55$, $p < .005$, $\eta^2 = .22$, and $F(1,11) = 24.91$, $p < .005$, $\eta^2 = .22$, respectively]. The linear trend accounted for 65.1% of the variance in the verbal condition and 60.2% in the haptic condition. The residual variance was not significant in the verbal condition [$F(8,88) = 1.65$, $p = .12$] but was significant in the haptic condition [$F(8,88) = 2.05$, $p < .05$, $\eta^2 = .16$]. Furthermore, the two learning conditions did not lead to different performances on the scanning task. As was reported for the sighted participants, the nature of the learning condition (verbal vs. haptic) had no effect on the overall scanning times for the late blind participants [$M = 1{,}226$ msec for the verbal condition, and $M = 1{,}647$ msec for the haptic one; $t(22) = -1.47$, $p = .64$].

As is shown in Figure 1B, times and distances were significantly correlated in both cases [$r(8) = .86$, $p < .01$, for the verbal condition, and $r(8) = .81$, $p < .01$, for the haptic condition]. There was no significant difference between the two values ($z < 1$).

Congenitally blind participants. Figure 1C shows the data for the congenitally blind participants, which clearly departed from those for the other two groups. The times

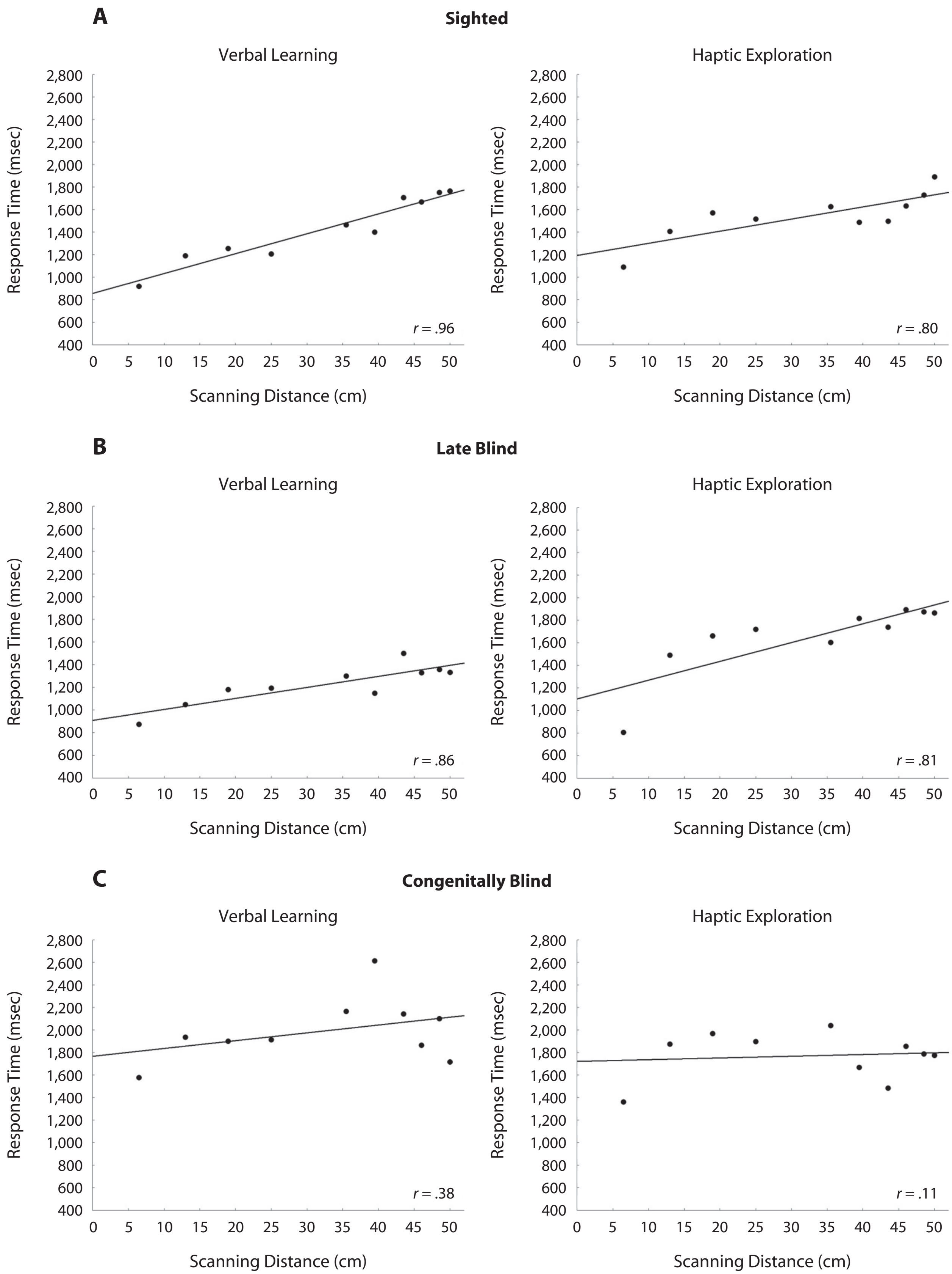

Figure 1. Experiment 1: Response times as a function of scanning distance after verbal learning (left) and haptic exploration (right) for sighted, late blind, and congenitally blind participants.

differed as a function of distances in the verbal condition [$F(9,99) = 3.06$, $p < .025$, $\eta^2 = .22$], but the best-fitting linear function did not reveal any sign of a linear component [$F(1,11) = 1.28$, $p = .56$]. In the haptic condition, the times did not differ significantly [$F(9,99) = 2.25$, $p < .10$]. Learning modality had no effect on scanning times ($M = 1{,}993$ and 1,771 msec, respectively; $t < 1$). Accordingly, neither of the two conditions displayed any significant correlation between scanning times and distances [$r(8) = .38$ and .11, respectively]. The two values did not differ from each other ($z < 1$).

Comparisons between groups. In the verbal condition, a one-way ANOVA revealed a marginally significant effect of groups (sighted, late blind, and congenitally blind) on the overall scanning times [$F(2,33) = 4.67$, $p < .08$]. Whereas times did not differ for the sighted and the late blind ($t < 1$), the congenitally blind participants' scanning times were significantly longer than those of the late blind participants [$t(22) = -2.95$, $p < .025$], but not those of the sighted [$t(22) = -1.99$, $p < .12$]. In addition, whereas the correlation coefficients did not differ between the sighted and the late blind groups ($z = 1.22$, $p = .11$), both were significantly higher than the coefficient for the congenitally blind group ($z = 2.89$, $p < .01$, and $z = 1.67$, $p < .05$, respectively).

In the haptic condition, a one-way ANOVA did not reveal any effect of groups on the overall scanning times ($F < 1$). Thus, following haptic learning, there was no difference between the three groups of participants with regard to their overall RTs in the scanning task. As in the verbal condition, the correlation coefficient between RTs and distances was smaller for the congenitally blind than for the sighted ($z = 1.85$, $p < .05$) and the late blind ($z = 1.90$, $p < .05$) participants. The coefficients did not differ between the sighted and the late blind groups ($z < 1$).

Discussion

Three groups of participants with distinct visual histories (sighted, late blind, and congenitally blind) were invited to use nonvisual modalities to learn a small-size spatial configuration, either by listening to a verbal description or by exploring the configuration haptically. After this learning process, they performed a mental scanning task. Their chronometric data revealed distinct patterns—namely, significant positive correlation between scanning times and distances for the sighted and late blind participants, but not for the congenitally blind.

The data for the blindfolded sighted participants replicated those reported previously (Denis & Cocude, 1992; Kerr, 1983) and demonstrated the ability of sighted participants to construct a mental representation of a spatial configuration. This representation was shown to preserve the topological organization of the scene and the metric relationships between the details of the configuration. The results attested that mental images generated from nonvisual modalities (verbal description and haptic experience) incorporate metric information about the spatial configurations they represent. In particular, our findings are in line with studies showing that spatial language can be converted into representations that are functionally equivalent to those formed from direct perception (e.g., Avraamides, Loomis, Klatzky, & Golledge, 2004; Denis, 2008; Klatzky, Lippa, Loomis, & Golledge, 2003; Mellet et al., 2002).

Like their sighted counterparts, the late blind participants performed well under both conditions, which indicated that their representations exhibited high structural isomorphism with regard to the described or handled configuration. The similarity of the patterns of data for the two groups is compatible with the assumption that similar processing mechanisms are applied to the spatial representations for both groups. The internal structure of their representations appears to include valid metric information, as attested by the consistently significant time/distance correlation coefficients.

The chronometric data for the congenitally blind group differed markedly from the patterns observed in the other two groups. The congenitally blind participants did not appear to construct a spatial representation of a small-scale configuration in which distances were consistently represented. Their response patterns did not reveal that they generated the kind of metrically accurate mental representations that the other two groups formed. Although they reached the learning criterion just as their counterparts in the other two groups did, their difficulty could probably have been overcome with additional learning of the configuration (see Denis & Cocude, 1992), but with similar learning opportunities, they seemed to experience a greater difficulty, as compared with their late blind counterparts. Their internal representations cannot therefore be considered to be equivalent to those of the sighted participants or to those with late-onset blindness.

One may legitimately wish to hypothesize about the type of spatial representations that can support such results. For example, if congenitally blind people do not metrically code a haptically learned stimulus, how do they code it? Note that our present investigation of internal representations was based on the use of a paradigm—namely, image scanning—that originally was designed to demonstrate the presence of metrically valid information in these representations. As such, this approach is not intended to assess representations other than those containing metric information. This means that we cannot make any claims about the nature of representations that do not appear to contain metric information. These issues have been discussed in studies showing that the acquisition of spatial concepts can be mediated by nonvisual sensory experience (e.g., Dulin, Hatwell, Pylyshyn, & Chokron, 2008).

To summarize, whereas late blind people appear to be able to construct representations that preserve the metric properties of verbally described or manually handled spatial configurations, the processing cost involved in the construction of metrically valid representations is higher for congenitally blind people. People who have had at least early visual experience appear to be able to transform the incoming information into visuospatial representations endowed with metric properties, like the visual images constructed by sighted participants in classic image-scanning experiments. The accessibility of representations derived from language and haptic exploration supports the assumption that the translation of inputs into analogue representations having a visuospatial substrate operates similarly in the late blind and the sighted groups.

The scanning data collected under the verbal condition are very similar to those found in earlier experiments using this methodology (e.g., Chabanne et al., 2004; Denis & Cocude, 1992). They also provide new information about the scanning task as executed by blind participants. The data from the haptic condition only partly match the results previously reported by Kerr (1983) and Röder and Rösler (1998). In line with Kerr's study, we recorded much longer scanning times for the congenitally blind participants than for the sighted controls. But Kerr's study reported a significant time/distance correlation for both sighted and congenitally blind participants, whereas our experiment did not confirm this correlation for our congenitally blind participants. As we mentioned in the introduction, a potential problem with Kerr's study is that although all 10 participants were reported to have been blind from birth, only 4 of them were said to be "totally blind," which created an unfortunate heterogeneity in the experimental group. The strict criteria we used to select 24 totally blind people as our early blind participants were intended to avoid including people with minimal or residual light perception. Furthermore, the comparability of the sighted and blind participants in our study was achieved by using exactly the same learning procedures, in contrast to Kerr's study, in which the blind people learned the configuration haptically, whereas the sighted learned it visually.

The discrepancy between our results and those in Röder and Rösler (1998) (who found a scanning effect after haptic learning in their blind participants) may be explained by differences in the learning procedure. In the Röder and Rösler study, the participants explored the configuration freely with both hands without any time limit, whereas in our study, we took care to move the hand of the participants from landmark to landmark at a controlled rate. This procedure was adopted in order to ensure similarity of learning times under the two conditions. In addition, it prevented the participants from using both hands to evaluate the interlandmark distances during learning (another important feature of the procedure that was intended to make the two conditions more comparable).

EXPERIMENT 2

In Experiment 1, the participants processed small-scale spatial configurations, which are typical of most image-scanning studies. Constructing a representation of such configurations may rely on several kinds of sensory modalities but essentially does not involve any active exploration on the part of the participants. The metric properties of proximal spaces that are experienced without any locomotor component might be especially difficult for congenitally blind people to encode. For them, the optimal conditions for constructing spatial representations presumably rely on body involvement (see Iachini & Giusberti, 2004; Loomis et al., 1993; Tinti et al., 2006). If this is true, congenitally blind people can be expected to perform better in tasks in which the acquisition of spatial knowledge is based on locomotion.

This question motivated Experiment 2, in which we used the scanning paradigm again, but with the objective of contrasting verbal and locomotor experiences as sources of learning. This entailed having the participants construct representations of more extended full-scale spatial environments, rather than the small-size configurations used in the previous experiment. In doing so, we expected that congenitally blind people would demonstrate their capacity to construct more accurate spatial representations than would sighted people when they learned an environment in which they were physically immersed but that no such difference would appear when they learned a verbal description.

This new experimental context opened onto a further question that was thought to be relevant to the issue of the representation of space by blind people—namely, the role of auditory information in assisting the creation of spatial knowledge (see Loomis, Lippa, Klatzky, & Golledge, 2002; Wanet & Veraart, 1985). To this purpose, we created an experimental situation suited to the investigation of blind people's capacities to construct spatial representations of an environment filled with sounds. The objective was to assess the structural properties of the spatial representations acquired by blind and blindfolded people in two situations—namely, listening to a verbal description of the locations of a set of sound sources and physically moving around the environment to spatially localize and position each individual source.

The procedure consisted of immersing the participants in a real environment large enough to permit locomotion. The participants were provided with a virtual audio sound scene; that is, we created the virtual experience of a spatial auditory scene consisting of an organized set of natural sources distributed in space. Using a virtual reality (VR) platform, we created auditory scenes and offered the participants the possibility of interacting directly with the different sound sources (approaching them, going away from them, walking around them, etc.). The VR platform included a tracking system that captured and recorded the motions of the participants while they navigated through the environment. Open circumaural headphones were used to render the virtual binaural auditory information to the participants, while allowing for direct vocal communication with the experimenter. The VR tracking system allowed the virtual auditory scene to remain stable in space, despite any displacements or head movements. The participants felt as though they were surrounded by sound sources perceived at precise positions, creating a coherent spatial environment, as is typically the case in natural environments with real fixed sound sources. The benefits of the VR platform included the possibility of controlling the exact geometric position of each sound, which could be changed dynamically without the need for repositioning any physical equipment.

After familiarizing themselves with the environment through one of the two modes (the verbal and locomotor conditions), the participants (sighted, late blind, congenitally blind) were tested with the scanning paradigm. Our prediction was that the locomotor experience within an environment would be more suitable to blind people's capacities than were the modes of acquisition used in the previous experiment and that this would result in a stronger time/distance correlation.

Method

Participants. Fifty-four participants took part in this experiment. They were selected on the basis of the same criteria as those in Experiment 1, with ages ranging from 21 to 63 years and with equal numbers of men and women. There were 18 participants in each group (sighted, late blind, congenitally blind). In each group, 9 participants were allocated to each of the two learning conditions.

Materials. A large-scale immersive audio virtual environment was created, in which the participants could explore and interact with virtual sound objects located within the room. The environment in which the experiment took place consisted of a room (both physical and virtual) in which six virtual (but realistic) sounds were located. The participants were immersed in a purely auditory virtual environment, limited by the inherent geometry of the real room. Acoustically, the virtual sources were in free space, since the VR system did not include any room reflections or reverberations. Although no room reflections were rendered, dynamic acoustic distance and orientation cues were provided, allowing for proper sound source localization. Therefore, although distance cues from a fixed position were not optimal, with locomotion, this effect was eliminated.

Sound sources were positioned on a horizontal plane slightly above the head of the participants, ensuring that sound levels did not become excessive when the participants stood right at the source positions. This situation was the equivalent of a real installation in an acoustically damped room with omnidirectional loudspeakers suspended above the plane of the listener's head. The height of the suspended speakers was adjusted relative to the height of each participant.

The participants were equipped with a head-tracker device, mounted on a pair of stereophonic headphones, as well as a handheld tracked pointing device, which made it possible for the experimenter to know in real time the positions and directions indicated by the participants. The experimenter sat outside the experimental room and had visual feedback of the entire scene through a graphic rendering. The experimental platform and the sound-processing architecture designed for the needs of the experiment have been fully described elsewhere (Afonso, Katz, Blum, Jacquemin, & Denis, 2005).

The experimental room was 4×6 m in size. The sound sources were located on the perimeter of a virtual circle 3 m in diameter, centered in the room. The following six familiar and distinct "domestic" sound samples were selected and assigned to positions that replicated the hour-coded positions of the landmarks used in the previous experiment: running water, a telephone ringing, a dripping faucet, a coffee machine, a ticking clock, and a washing machine.

Procedure. In the preliminary phase of the experiment, the participants filled in a questionnaire to provide information about their educational and sociocultural backgrounds and, for the blind participants, about the origin of their blindness. They also passed an audiometric exam to verify that they had no appreciable hearing impairment. Lastly, each participant followed a short selection protocol for choosing the most appropriate head-related transfer function from an existing database in order to provide an optimal individualized rendering of the binaural synthesis in the learning phase (cf. Afonso et al., 2005; Begault, 1994).

The participants were then led into the experimental room. The sighted participants were blindfolded before entering the room and remained blindfolded until the end of the experiment, so as to ensure that no group had any visual knowledge of the room. Once in the room, the participants were guided by the experimenter along the perimeter walls to enable them to imagine the size and shape of the room. The participants were then asked to sit on a fixed chair that would be the reference point for the rest of the experiment. The chair was placed midway along one wall of the room, with its back to the wall. When the participants were standing or sitting at the chair position, they knew that their work space was directly in front of them and that they were facing the center of the room, with the front–back axis of their body parallel to the side walls.

At the beginning of the learning phase, the participants in both conditions were led by the experimenter to the center of the virtual circle (i.e., the center of the room). They were informed that they had just traveled a distance of 1.5 m (the radius of the circle). When positioned at the center of the circle, the verbal condition participants were informed that their body was oriented along the 6 o'clock–12 o'clock axis and that they were facing the 12 o'clock position. Then, via the headphones, they heard the sound of water running from a tap, spatialized so as to be perceived just above their head. The sound lasted 3 sec. The experimenter informed them that they should mentally place this sound on the periphery of the virtual circle surrounding them at the 11 o'clock position. The same procedure was used for the remaining five sounds, following the clockwise sequence used in the corresponding condition in Experiment 1. After listening to the six sound sources, the participants were again presented with the sounds in the same order and were asked to verbally indicate the hour-coded position of each sound. The entire procedure was repeated until the participants could recall the position of each sound correctly.

The locomotor condition participants were positioned at the center of the virtual circle, with the same body orientation as for the verbal condition. When the first sound was played, it was spatialized so as to be perceived as coming from its nominal position on the circle (e.g., running water at the 11 o'clock position at a distance of 1.5 m). The participants were asked to physically move about the room and position themselves just under the location of the sound emitted (all sound sources were placed on a plane at a fixed distance above the participants' heads). From there, the participants were led back to the center of the circle by the experimenter. This procedure was repeated for all six sound sources successively. The participants' learning of the sound source positions was evaluated by inviting them to listen to each sound (spatialized directly above their head) and use the tracked pointer to indicate the exact location of the sound as they had just learned. This was repeated for all six sounds. The whole procedure was repeated until all six pointing responses were within 10º of the exact position of the corresponding sound. The radial distance was not used in this study, since all the sources were positioned at the same distance from the center of the circle.

In the test phase, the participants were tested on the mental-scanning task, using the same method as that in Experiment 1. They were led into another room, where they were first invited to review mentally the learned environment and the position of each sound source. The trials then consisted of the participants' first hearing a sound, which was part of the learned environment, and then a second sound. When this second sound was part of the environment (*true* trials), the participants were asked to imagine a little spot moving from the first to the second source in a straight line, at a constant speed. They had to press a key with their dominant hand when the mental displacement had been completed. When the second sound was not part of the environment (*false* trials, in which five distractor sounds were used), they had to press another key with their nondominant hand. Because of the length of time taken to learn in the virtual environment, a shorter version of the scanning task was used than in the previous experiment, with a total of 40 scanning trials (instead of 60).

Results

Only the times for the correct true items were included in the analysis. Outliers were eliminated, following the same procedure as that in Experiment 1. Outliers occurred on 4.7% of the trials. Due to a technical error, the values for one of the distances were not recorded, and this resulted in data based on 9, instead of 10, distinct distances. For each participant and each distance, we averaged RTs over the trials.

In the analyses reported below, we corrected p values to control for familywise error rate, following the same procedure as that in Experiment 1. Separate one-way repeated measures ANOVAs showed that distance had an overall significant impact on scanning times [$F(8,208) = 12.67$, $p < .001$, $\eta^2 = .33$, for the verbal condition, and $F(8,208) = 4.81$, $p < .001$, $\eta^2 = .16$, for the locomotor condition]. In both conditions, times increased linearly with increases in distance [$F(1,26) = 97.12$, $p < .001$, $\eta^2 = .32$, and $F(1,26) = 32.37$, $p < .001$, $\eta^2 = .14$, respectively]. The linear trend in the verbal condition accounted for 95.8% of the variance due to the effect of distance, and the linear trend in the locomotor condition accounted for 84.2% of the variance. The residual variance was not significant in both conditions (Fs < 1). Following verbal learning and locomotor learning, scanning times increased linearly with increases in distances [$r(7) = .98$, $p < .01$, and $r(7) = .92$, $p < .01$, respectively]. Overall, there was no significant difference between the time the participants needed to perform mental scanning in the verbal and locomotor conditions [$M = 1{,}443$ and 1,701 msec, respectively; $t(52) = -1.16$, $p = .75$], and no significant difference between the time/distance correlation coefficients ($z = 1.22$, $p = .11$).

As in Experiment 1, we then concentrated on the contrast between the two conditions for each group taken separately. The main measurements here were the correlation coefficients between scanning times and distances.

Sighted participants. After the learning of verbal information, times varied significantly with distances [$F(8,64) = 3.59$, $p < .01$, $\eta^2 = .31$], and the linear component was significant [$F(1,8) = 24.88$, $p < .005$, $\eta^2 = .31$]. The linear trend explained 86.7% of the variance due to the effect of distance. The residual variance was significant [$F(7,56) = 3.81$, $p < .01$, $\eta^2 = .06$]. However, as is shown in Figure 2A, RTs and distances were significantly correlated after verbal learning [$r(7) = .93$, $p < .01$]. In contrast, after locomotor learning, distance had no effect on scanning times ($F < 1$), and there was no trace of any correlation between RTs and distances [$r(7) = .17$, $p = .35$]. Learning modality had no effect on the overall scanning times, with $M = 1{,}539$ msec for the verbal condition and $M = 1{,}486$ msec for the locomotor condition ($t < 1$). The strength of the correlation was significantly higher for the verbal than for the locomotor condition ($z = 2.58$, $p < .005$).

Late blind participants. The effect of distance on scanning times was significant both after the learning of verbal information [$F(8,64) = 5.14$, $p < .001$, $\eta^2 = .39$] and after locomotor learning [$F(8,64) = 7.08$, $p < .001$, $\eta^2 = .47$], with significant linear effects of distance [$F(1,8) = 38.03$, $p < .001$, $\eta^2 = .40$, and $F(1,8) = 46.60$, $p < .001$, $\eta^2 = .45$, respectively]. The linear trend accounted for 92.5% and 82.3% of the variance of the effect of distance, respectively. In both conditions, the residual variances due to the effect of distance were significant [$F(7,56) = 3.07$, $p < .05$, $\eta^2 = .05$, and $F(7,56) = 10.01$, $p < .001$, $\eta^2 = .15$, respectively]. The learning modality had no effect on the overall scanning times ($M = 1{,}518$ and 1,779 msec, respectively; $t < 1$).

As Figure 2B shows, a strong time/distance correlation was found for both learning conditions. The correlation coefficients reached the values of $r(7) = .96$, $p < .01$, after verbal learning, and $r(7) = .91$, $p < .01$, after learning by locomotion. There was no difference between the two values ($z < 1$).

Congenitally blind participants. Figure 2C shows the corresponding data for the congenitally blind group, which reveal a pattern similar to that for the late blind group. Times varied significantly with distances [$F(8,64) = 7.16$, $p < .001$, $\eta^2 = .47$, for the verbal condition, and $F(8,64) = 3.44$, $p < .01$, $\eta^2 = .30$, for the locomotor condition], and the linear component was significant in both cases [$F(1,8) = 48.94$, $p < .001$, $\eta^2 = .49$, and $F(1,8) = 24.70$, $p < .005$, $\eta^2 = .31$, respectively]. The linear trend accounted for 85.4% of the variance in the verbal condition and for 89.9% in the locomotor condition. The residual variance was significant in the verbal condition [$F(7,56) = 8.34$, $p < .001$, $\eta^2 = .13$] and marginally significant in the locomotor condition [$F(7,56) = 2.78$, $p = .06$]. Overall, scanning times did not differ significantly for the two conditions, with $M = 1{,}283$ and 1,836 msec, respectively [$t(16) = -1.46$, $p = .72$].

Following verbal learning, the correlation coefficient between times and distances reached the significant value of $r(7) = .92$ ($p < .01$). Following locomotor learning, the correlation coefficient was $r(7) = .95$ ($p < .01$). These two values did not differ significantly from each other ($z < 1$).[2]

Comparisons between groups. In each learning condition, the overall scanning times did not significantly differ for the three groups of participants (Fs < 1), and none of the specific comparisons in each condition reached significance (ts < 1). In the verbal condition, the correlation coefficients between scanning times and distances did not significantly differ from one another (zs < 1). However, in the locomotor condition, the coefficient for the sighted participants was smaller than the coefficients computed for the late blind and the congenitally blind participants ($z = -3.07$, $p < .005$, and $z = -2.87$, $p < .005$, respectively). There was no difference between the coefficients for the last two groups ($z < 1$).

Discussion

Blindfolded sighted, late blind, and congenitally blind participants were invited to perform an image-scanning task after learning an environment in which they were immersed, either by processing a verbal description or by locomotor exploration of the environment. There were contrasting outcomes for the sighted and the blind participants. In all three groups of participants, verbal information seemed to be transformed into spatial representations that incorporated the metric distances between different locations in a navigable environment. On the other hand, there was a clear contrast between the blind participants' representations and those of their sighted counterparts when learning was based on locomotor experience.

Not surprisingly, after verbal learning, the chronometric data for the sighted participants revealed that their representations did contain valid metric information. Although

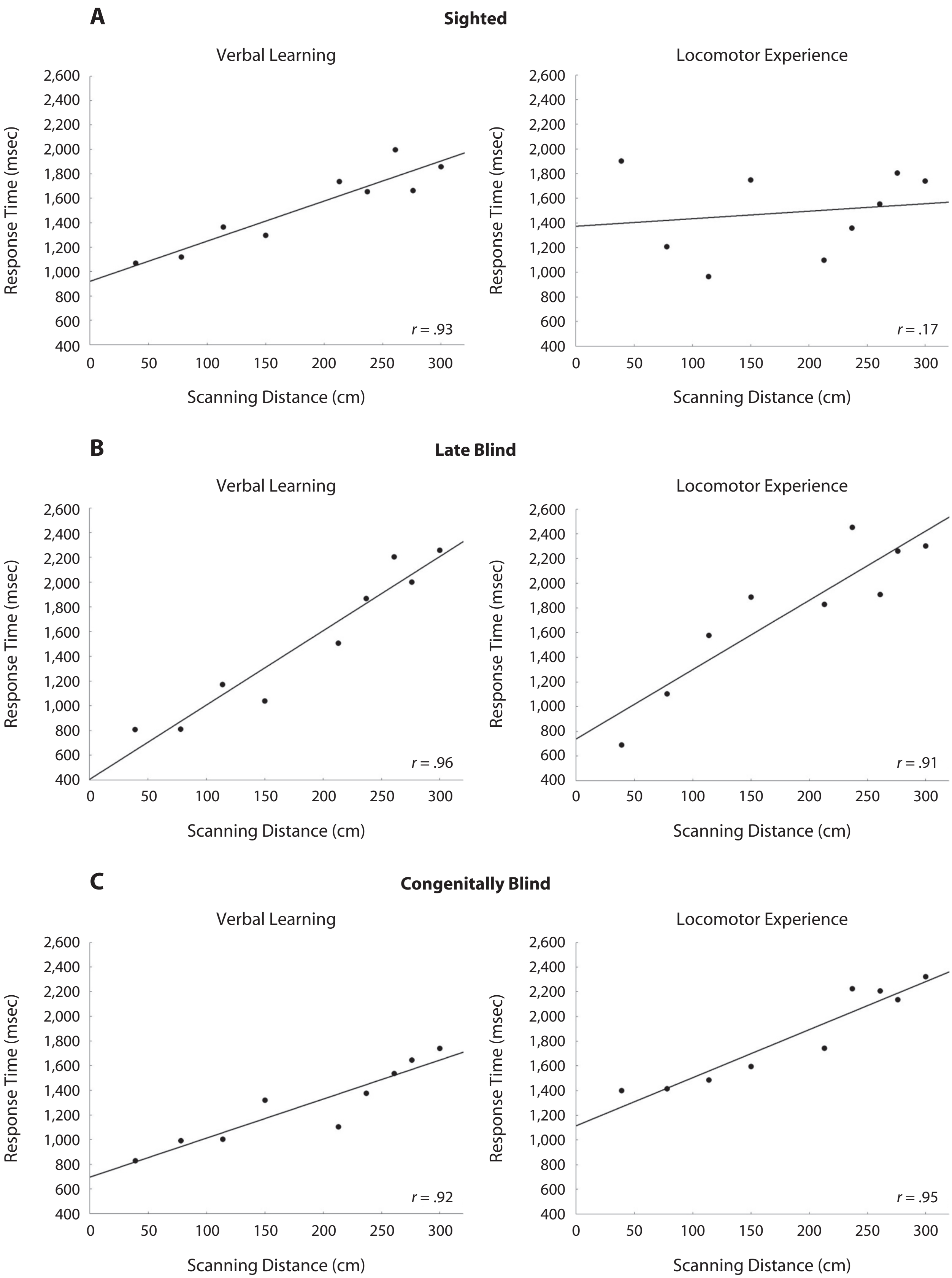

Figure 2. Experiment 2: Response times as a function of scanning distance after verbal learning (left) and locomotor experience (right) for sighted, late blind, and congenitally blind participants.

learning took place in an environment that was different from that in Experiment 1, one could expect that the mental processes used to construct a mental representation of the environment from a verbal description would make use of similar cognitive resources. On the other hand, the cognitive difficulty experienced by sighted people in constructing a metrically valid representation of the environment by means of navigation while blindfolded was evident. Sighted people are not prepared to elaborate mental spatial models using such an unfamiliar procedure. The resulting effect is that the metric information is simply not encoded in their mental representation (at least, after the amount of learning permitted in this experiment).

The late blind participants handled verbal information in a manner quite similar to that for the sighted ones. Metric information was accurately represented in their images, resulting in the typical scanning effect. They differed from the sighted people in showing almost the same ability to encode metric information when learning relied on locomotor experience. The distances explored by navigation were well exploited, and they contributed to the construction of an efficient, realistic representation of the environment. However, like the sighted participants, they took longer to review a representation based on locomotor experience than one based on verbal inputs.

The pattern of results of the congenitally blind participants was in sharp contrast to those of their counterparts in Experiment 1, whose responses reflected a poor internal organization of the representation constructed from haptic exploration, the condition under which the sighted participants showed proficiency. In the present experiment, the pattern was reversed, in the sense that the blind participants showed clear superiority over the sighted participants when blindfold locomotion was used during learning. The sensory inputs provided by this learning procedure were efficiently encoded by the blind participants, whereas the sighted participants were not able to convert that information into analogue-like representations.

To summarize, after verbal learning, all the participants demonstrated their capacity to construct the mental representation of a purely audio scene. This representation preserved the topological organization of the scene and the metric relationships between the sound sources. Permanent blindness did not prevent people from constructing representations in which metric information was validly represented. However, temporary sightlessness placed sighted people in a situation in which they demonstrated particular difficulty in elaborating a metrically accurate mental representation of an environment learned by locomotion.

GENERAL DISCUSSION

In the experiments reported above, the results of mental-scanning tasks showed that sighted people, those with late-onset blindness, and congenitally blind people displayed different patterns, depending on the nature of the learning situation. After haptic learning, the congenitally blind participants were at a disadvantage. After locomotor learning, they clearly outperformed the sighted participants. In the case of permanent blindness, what seems to be crucial for constructing a consistent, metrically realistic, and valid representation of an environment is for the spatial information to be encoded on the basis of people's most reliable currently functional sensorimotor system.

The assumption of analogue-like spatial representations is supported only when the mode of acquisition of spatial information is adjusted to the individual capacities of people who are processing that information. For a sighted person, there is little doubt that the most efficient way of acquiring spatial information is sight, but also language in some cases (as shown by both the present study and previous ones). The analogue nature of the representation is achieved by blind people only when locomotion and sensorimotor experience are involved in creating the representation.

The case of the congenitally blind people deserves special attention. In this study, they appeared to be relatively impaired in the task involving haptic learning (in contrast with their proficiency with tasks following locomotor learning). Their impairment in performing this specific task may be surprising if one considers that haptics are an important capability for blind people, even though it is well established that haptic knowledge suffers to some extent when it is not backed up by sight (e.g., Ungar, 2000). One explanation for the difficulty experienced by the congenitally blind may reside in a specific feature of the methodology used in Experiment 1. In the learning phase, the configuration consisted of a vertically oriented disk (rather than one placed horizontally on the tabletop plane). The vertical presentation was adopted here from Kerr's (1983) original study, for the purpose of comparability. However, the horizontal orientation may be more standard and, thus, more natural for haptic exploration. We must therefore consider that this 90º offset has introduced noise into the subsequent mental-scanning task and that this accounts for the poorer performance.[3]

We should also emphasize that the experimental situations created in our experiments are illustrative of the classic contrast between *near* and *far* space. Whereas the former is typically described as a *manipulatory* space, the parts of which can be explored without any need for a person to physically move his or her body, the latter relates to large-scale environments, the exploration of which usually requires locomotion. In this respect, for congenitally blind people, the relevant distinction could be between proximal space and space that invites them to move. These people demonstrate their capabilities fully in the latter type of space. This is to say not that the congenitally blind do not have a functional haptic system, but that it is the scale of an environment, rather than the learning modality, that is critical. This alternative explanation deserves more systematic exploration, given the well-documented differences between small-scale and large-scale spatial abilities (see Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006).

The distinction between small- and large-scale spaces may also help to explain the apparent discrepancy between (1) the difficulty experienced by the congenitally blind participants when they had to construct the representation of a small-size configuration from a verbal description (Experiment 1) and (2) their good performance with the same type of description applied to a real immersive environment in which a person is surrounded by the landmarks (Experiment 2). The latter situation appears to facilitate the construction of a representation in which metric information is easy to encode.

The results of the present study also contribute to the current discussion about the nature of the mental representations of space. In Experiment 1, the similarity between the blindfolded sighted and the late blind participants, as compared with the early blind, invites an interpretation in terms of the latter group's not being able to use visuospatial processes and supports the assumption that the inputs lead to representations mediated by a visuospatial substrate. However, this assumption does not account for the data collected from the late blind participants in our experiments. The concept of a common spatial substrate, independent of visual properties, warrants consideration here. A growing body of evidence suggests that the inputs provided during the encoding of spatial information may lead to functionally equivalent (amodal) representations, such as the "spatial image" advocated by Loomis et al. (2002), which supports behavior in an equivalent manner independently of the encoding modality (see also Bryant, 1997; Klatzky et al., 2003; Knauff, 2009). This perspective would offer an alternative hypothesis to explain some of the similarities between learning modalities and between groups reported above.

More generally, our study adds to the evidence that mental imagery can be dissociated from visual perception (e.g., Cornoldi & Vecchi, 2000; Vecchi, 1998). Our findings also confirm that in the absence of visual perception, gathering spatial information provided by other modalities can contribute to the creation of metrically valid internal representations. However, even though visual experience is not a necessary condition for constructing such representations, using alternative processes has a cost (see Tinti et al., 2006). The limitations associated with this additional load can only be circumvented if the alternative processes match people's current capacities, such as sensorimotor encoding by congenitally blind people.

Finally, this study has shown the feasability of using virtual audio scene rendering for locomotion in a full-scale navigable space for the purpose of investigating cognitive spatial representations. We have shown the efficacy of 3-D audio in driving the elaboration of spatial mental representations in conjunction with movement (and even without it). As a viable mode of nonvisual environmental access, this technology may be a benefit to further studies—in particular, those involving visually impaired people.

AUTHOR NOTE

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NOTES

1. Although this interpretation of image scanning has been a matter of controversy (cf. Pylyshyn's [1973, 1981] proposition-based theory and his further claims for the cognitive penetrability of images), more recent empirical data have provided arguments in favor of the correlation between scanning time and scanned distance as a genuine signature of the analogue character of mental images (e.g., Denis & Carfantan, 1985; Denis & Kosslyn, 1999; Pinker et al., 1984).

2. The latter coefficient differed significantly from the correlation coefficient for the congenitally blind participants in the haptic condition in Experiment 1 ($z = -3.03, p < .001$). There was no difference between the corresponding coefficients for the late blind participants ($z < 1$).

3. As was aptly pointed out by a reviewer, people make this visual transformation from vision on a daily basis—for instance, seeing a map on the computer screen or wall and then rotating it into the terrain perspective in order to navigate. However, such transformations are rarely done from haptic exploration, since reading Braille or tactile maps is typically done on a horizontal surface.

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