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**On prior visual experience in mental map navigation using
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SAGE

Amandine Afonso-Jaco^{1,3} and Emma Adam¹ and Brian F.G. Katz²

1 Introduction

This study concerns the properties of mental representations of space developed by visually impaired people. The primary question this work attempts to address concerns the spatial mental perspective representations naturally elaborated by blind people.

A large number of studies have been interested in the nature of the mental representations of individuals in general (not specifically involving blind individuals) and have concluded that the knowledge of environments of the allocentric type appeared only after the discovery of the environments step by step (discovery of landmarks, identification of the different paths globally linking these landmarks, then by integrating the metric relations between these different landmarks), allowing to pass from the elaboration of an egocentric mental representation to an allocentric one (Siegel and White 1975; Denis 2017). Thus, the spatial model constructed is progressively elaborated, becoming more complete each time by combining the information resulting from the motor exploration of this environment but also from all the other senses brought into play, initially the visual sense which plays a major role, offering the possibility of accessing all the information at once. This progressive and hierarchical conception is, however, questioned by works showing early acquisition of knowledge that is assumed to be at a higher level (Huttenlocher et al. 2008; Nys et al. 2015). However, in the case of blind people, whether or not they have benefited from prior visual experience, the appropriation of space cannot take place in this manner. Information is principally acquired sequentially, allowing the discovery of spatial references one after the other, possibly extending to bi-manual exploration with two concurrent streams of tactile information.

Most studies, even if they do not all go in the same direction, agree in suggesting that blind people are capable of representing their environment spatially, whatever the modalities of acquisition of this environment (see Thinus-Blanc and Gaunet (1997); Dulin et al. (2008) for reviews). On the other hand, some results suggest that, depending on the elaboration, an allocentric mental representation would be particularly difficult (Denis 2017; Pasqualotto et al. 2013), or even impossible, in the case of people who are blind from birth in mental distance exploration tasks*, for example, see Annex (Afonso 2006).

We note that in the vast majority of studies on spatial representation by the blind, participants have been asked to create a mental representation of a map, placing the participant in a ‘flyover’ mode to solve the experimental task (Afonso 2006; Afonso et al. 2010; Chabanne et al. 2004; Picinali et al. 2014), compared to the limited studies employing egocentric exploration (Picinali et al. 2014; Afonso et al. 2010; Afonso-Jaco and Katz 2022).

Looking in more detail, the set of studies by Afonso et al. (2005, 2010); Afonso-Jaco and Katz (2022) compared distance comparison task results between verbally described, small (haptic table-top vertically mounted map), and large (room-scale locomotive/spatial-auditory) environments. Results showed different performances depending on prior visual experience and learning conditions, with late-blind participants performing best with locomotive egocentric learning. Specifically, early-blind participants made significantly more errors in the case of small differences in distances than late-blind and blindfolded-sighted participants. Furthermore, whereas following learning of a small size configuration, early-blind participants took significantly longer than blindfolded-sighted participants to compare distances, this was no longer the case after learning the spatial configuration in the immersive environment.

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*A “mental distance exploration task” involves activities aimed at studying how individuals mentally manipulate and navigate spatial information. This may include tasks such as Spatial Reasoning, Spatial Memory, Mental Rotation, Perspective-Taking, Virtual Navigation, and Spatial Imagery. By examining performance on these tasks, researchers can gain insights into various aspects of spatial representation, such as mental imagery, spatial reasoning abilities, and the underlying cognitive processes involved in navigating and understanding spatial environments.

Using similarly scaled, though simpler environments (horizontally mounted table-top and room-scale locomotive/haptic environment), Iachini et al. (2014) approached allocentric/egocentric perspectives differently, considering allocentric (distance between objects) versus egocentric (distance to myself/reference position) distance comparisons. Results showed that congenitally blind people had more difficulty with allocentric tasks with respect to late-blind and sighted participants, being more pronounced in the large-scale than small-scale environment. Egocentric task performance was better than allocentric for all groups, more so for the small-scale environment. While they concluded that in the absence of prior visual experience, egocentric spatial representations were “favoured”, this judgement would appear to be based on task performance, not on preference.

In contrast, Pasqualotto et al. (2013), using a large (room-scale locomotive/haptic) environment, investigated whether the ability to use an allocentric reference frame is subject to visual experience. After exploring the environment, participants were prompted to an allocentric spatial representation through a tactile map. Tasks examined the reported angular position of learned objects relative to other objects (allocentric) or positions along the learned route (egocentric). Congenitally-blind participants performed better in egocentric tasks, while late-blind and blindfolded-sighted were better in allocentric tasks. In addition, for egocentric tasks, congenitally-blind participants performed better than late-blind and blindfolded-sighted, while in allocentric tasks, late-blind and blindfolded-sighted performed better than congenitally-blind participants.

It should be noted that the first two studies did not actually compare participants’ perspectives; they only inferred perspectives from the presentation method. The third study imposed different perspectives and evaluated associated performance. In contrast, the current study was designed to allow participants to freely employ an allocentric or egocentric perspective, realising the same task, enabling an evaluation of this *preference* via analysis of the results rather than being procedurally imposed.

1.1 Imposed mental map perspective

Several authors have put forward that one of the problems of so-called laboratory experiments is imposed by instruction of a specific type of resolution of the experimental task, thereby imposing the *strategy* to be used by participants, which can be biased to those who are more familiar with alternative strategies (Thinus-Blanc and Gaunet 1997; Cattaneo and Vecchi 2011). This can result in a conflation between ability, competence, and performance, as highlighted by Millar (1994). We can ask ourselves then, what would be the results obtained in tasks of mental scanning or mental comparison of distances if the participants were allowed to “navigate” mentally without constraints imposed by the instruction protocol (contrary to e.g. “Imagine yourself walking from A to B...”). In other words, if the instructions when comparing two distances *did not oblige* participants to take an allocentric perspective, would they tend to compare two distances corresponding to path lengths, or would they naturally take the allocentric perspective, as it has been imposed so far in the literature? This is the object of the current study.

1.2 Open perspective design

Unlike previous studies, without obstacles on the maps, adding obstacles can offer different correct responses depending on the mental representation perspective employed for judging the distances between objects. For example, the direct linear distance \overline{AB} may be shorter than \overline{BC} , but if an obstacle is placed between A & B then the route around said obstacle results in a path that is longer than \overline{BC} , meaning that, depending on the strategy (walking versus flying) the choice of the shortest path differs.

We subjected participants to learning spatial environments, representing a convoluted corridor path. Along this path, several landmarks were placed. The task consisted of creating a mental representation of this environment as precisely as possible by memorising the path’s structure and the different landmark positions. Participants then solved several tasks. The first is an immediate recall task, verifying that all the notable landmarks have been memorised. The second is a mental comparison of distances task, with the particularity of specifically not prescribing the use of an allocentric type of representation, as is often the case in the literature, but rather allowing participants to intuitively rely on the type of mental perspective that would naturally allow them to solve the experimental tasks. Finally, participants reconstruct the layout of the landmarks within a model of the environment based on their developed mental representations, providing a global metric of a mental map’s geometric quality.

The remainder of the manuscript is organised as follows. Section 2 presents the experimental hypotheses, methods, and design. Section 3 analyses the various task response results. This is followed by Section 4, situating the obtained results in the context of previous studies.

2 Experiment

This study examines the representations of spatial configurations constructed by late-blind, early-blind, and blindfolded-sighted individuals following haptic exploration. The aim is to reveal the type of mental perspective (allocentric or egocentric) that would come naturally to participants to achieve spatial mental tasks. The instructions purposely do not give any explicit directive on the type of perspective to be used during the resolution of the experimental tasks, contrary to what is classically used in mental distance comparison tasks (Afonso 2006; Denis and Cocude 1992; Noordzij et al. 2006; Picinali et al. 2014). Participants are, therefore, entirely free to resolve the task using an allocentric (*Euclidian*) or egocentric (*navigational*) mental map.

After having interviewed specialists in visual impairment (i.e. locomotion instructors, Braille trainers, researchers in visual impairment, and associations of visually impaired people) and blind and visually impaired people, it appeared to us that the supports, whether 3D printed or thermoformed, were used interchangeably. Recent research has shown that the increase in tactile contrast made possible by 3D printing could make exploration easier, especially for EBs and BSs (Bleau et al. 2023). In that study, low-resolution maps used 2D abstract symbols (e.g. lines to model staircases), while high-resolution maps used 3D direct symbols (e.g. miniature staircases). The study by Wabiński et al. (2020) has examined terrain-type maps

1 and the potential advantages of 3D printed maps of
2 traditional tactile maps used currently in classrooms for the
3 visually impaired. However, to our knowledge, no particular
4 attention had been paid to evaluating the potential impact
5 of one of these supports on the characteristics of the
6 mental representations elaborated, considering the different
7 resolution or level-of-detail capabilities between the two
8 support types without modifying the information format.
9 We were interested, therefore, in examining if the mental
10 representations produced from haptic exploration of an
11 interior spatial environment could be influenced by the tactile
12 support used to characterise this environment.

13 The following hypotheses are proposed and evaluated by
14 the current study:

- 15
16 H1 The approach to solving spatial mental tasks, when not
17 explicitly specified in the instruction, is individually
18 specific and influenced by early visual experiences.
19 We hypothesize that a preponderant preference for an
20 egocentric perspective in the mental exploration of
21 spatial maps, in the absence of specific constraints,
22 will be observed in individuals with early blindness. In
23 contrast, individuals with prior visual experiences are
24 more likely to employ an allocentric mental mapping
25 strategy.
- 26 H2 Providing participants with the freedom to select
27 their preferred perspective, whether allocentric or
28 egocentric, does not result in a performance advantage
29 for either perspective.

30
31 Taking the position that more precise tactile maps are
32 expected to enhance participants' comprehension of the
33 environment and increase the precision of their mental
34 representations, we propose a final hypothesis concerning the
35 experimental physical interface:

- 36
37 H3 The metric properties of mental representations are
38 affected by the level of environmental support during
39 learning, impacting response time, the percentage
40 of correct answers, and the precision of object
41 positioning within learned spatial configurations. This
42 difference will be more significant with inexperienced
43 users.

44 2.1 Design

45 The experimental design invites participants to haptically
46 explore virtual indoor environments (*scenarios*) using tactile
47 maps (*support*). In each map scenario, Object markers were
48 positioned at given landmark positions, or *points of interest*
49 (POIs). Following this exploration learning phase, three
50 tasks assessing simple memory processes or more complex
51 processes related to constructing their mental representation
52 were performed. Participants had to resolve a free recall of
53 POIs, carry out a series of mental comparisons of distance
54 tasks, and finally, reposition the POIs within their initial map,
55 as detailed in Section 2.2.

56 2.2 Methods

57
58 2.2.1 *Task overview* After the learning phase, tasks
59 assessing simple memory processes or more complex
60 processes related to constructing a spatial model (inferences)

were performed. These tasks, involving more or less the
egocentric or allocentric perspective, are classically used
in literature (see Péruch et al. (2006); Gyselinck et al.
(2006); Picucci et al. (2013) for some examples). Thus,
a free recall of objects (simple memory task), a distance
comparison (allocentric or egocentric perspective according
to the participant's implicit choice), and a task in which
participants had to indicate where objects were on the initial
plan (allocentric) as a final check were performed (Afonso
et al. 2010; Grison and Afonso Jaco 2020).

Free recall tasks :

The free recall of objects is a simple memory task used
to evaluate if elements are encoded in memory. This is
used in the literature for sighted participants as they learn
the object's spatial arrangement by visual exploration or
under a verbal format (Nys et al. 2015; Picucci et al. 2013;
Meilinger and Knauff 2008), or for blindfolded participants
after a sensory-motor exploration (Grison and Afonso Jaco
2020). This allows for verification that all elements have
been correctly memorised and that if they do not appear in
the reconstructions, it will be a problem of placement, not
knowing where it is, rather than not remembering that such
and such object was in the list.

In the current study, participants are evaluated before
performing the experimental tasks on their success in
recalling the learned environment. To ensure that participants
have incorporated the environment under study into their
working memory, a free recall task of the points of interest,
irrespective of spatial configuration, is employed. If recall
rates are insufficient, additional learning can be performed,
or the subject can be excluded if they appear unable to
accomplish the memory task.

Mental comparison of distance tasks :

A paradigm widely used to interrogate the analogical
character of mental representations is that of the mental
comparison of distances. Denis and Zimmere (1992) took
the material proposed in the mental scanning task, a circular
island (Denis and Cocude 1989), and asked participants,
as in the task described above, to learn the configuration
of the island and the position of different landmarks.
After learning the configuration, participants were asked to
mentally compare the distances between pairs of landmarks
(e.g., "is the distance between the harbour and the creek
greater than the distance between the harbour and the
lighthouse?"). Responses and associated response times
were recorded. This experiment was particularly interesting
because it allowed for a right or wrong response, a benefit
compared to the alternative mental scanning paradigm,
briefly described in the Annex for reference. Results from
the mental comparison of distance tasks have shown that
individuals process large distance differences more quickly
than small ones and that they make fewer errors in judgement
for large differences in distance than for small ones (Denis
and Cocude 1992, 1997), i.e., the larger the difference
between two distances, the shorter the response time, and the
higher the percentage of correct responses.

This corresponds to what has been observed in
psycho-physics, confirming the symbolic distance effect
phenomenon, according to which judgements of difference
(e.g., the difference in size) between objects evoked from

memory requires less time as the magnitude of the judged difference increases (Moyer 1973; Paivio 1975). This task was first proposed to people who were blind from birth, late-blind, and blindfolded-sighted by Afonso et al. (2003). Results showed that, after verbal description, tactile exploration, and locomotor exploration in a real or virtual environment, all participants, regardless of their prior visual experience, showed results similar to those obtained in the literature for sighted people, *i.e.*, the greater the difference between two distances, the shorter the response time and the higher the percentage of correct responses (Afonso 2006; Afonso et al. 2003; Noordzij et al. 2006; Picinali et al. 2014). This work agrees with the idea that the mental map developed by blind individuals, whether born blind or becoming blind later in life, preserves well the metric relations between the different objects present in the learned spatial environment.

A question has been raised regarding the impact of varying the learning perspective (egocentric or allocentric) on the preservation of metrics in mental representations of spatial configurations. Building on the work of Denis and Cocude (1989), Chabanne et al. (2004) used a paradigm to investigate the influence of learning modality (visual or verbal) and representation type (egocentric or allocentric) on mental representations of a spatial environment. They designed four learning conditions: “flyover-visual,” “visual route,” “fly-by-verbal,” and “path-verbal.” Participants explored the distances between landmarks in a circular garden with varying distances. Results revealed that participants’ response times increased linearly with the distance to be mentally explored, regardless of the experimental condition.

Noordzij et al. (2006) performed a similar mental distance comparison task with blind participants and showed that blind participants achieved the same pattern of results as sighted participants but that, unlike sighted participants, they performed better after listening to an egocentric description than after listening to an allocentric description.

Reconstruction task :

Previous research in the spatial understanding of architectural spaces used physical reconstructions (Picinali et al. 2014), comparing key points in the architectural reconstructions for analysis using bidimensional regression¹ (Friedman and Kohler 2003).

The reconstruction task ensures that after the manipulation, the mental model used by the participants is still of a nature to have allowed them to respond to the tests. If the person has incomprehensible results on the tests and, in this task, the reconstruction quality is very poor, then they are among the people to be eliminated from the panel. On the other hand, if their results in the reconstruction task are good, one must reexamine the test results to identify the issue.

Interpreting such analysis can be difficult if the number of reference points for the same map varies between participants. To ensure that all reconstructed maps had the same number of reference points, they were asked to reconstruct the positions of the 10 POI elements on the map. Photographs of the maps with constructed POI positions were taken, with the coordinates of POIs extracted and then used for bidimensional regression, thereby providing an overall metric comparing the spatial arrangement of the ensemble of POIs to the original reference map positions.

2.2.2 Materials

Scenarios: Four imaginary indoor corridor environments were created, representing a path with various landmarks along the way. Each scenario is defined by a map represented by a corridor (60 m length, 2 m width) comprising four turns (60°, 90°, 90° and 120°) and passing through a “room” (5 × 5 m). These maps were algorithmically generated (see Zagala (2022) for details). These common parameters were used to generate maps with similar structures and complexity to facilitate comparisons. The corridors’ compact and convoluted nature ensured that the resulting inter-POI Euclidean distances were different enough from the navigation distances. Four maps were selected from the randomly generated results, shown in Fig. 1.

Objects: Forty landmark terms were selected for POIs in the experiment. They were common objects, small, and manipulable (*e.g.* ball, pen, shoe, or key) so that there would be no conflict of plausibility with their existence at random positions. All objects were rated highly as being “really graspable” according to Guérard et al. (2014) database (as noted on a 7-point scale, $M = 6.9/7$; $SD = 0.23$; $Min = 6.75/7$; $Max = 7/7$). All were represented by identical markers not to induce a predefined representation of the objects to be memorised. The list of the objects is given in Tab. 1.

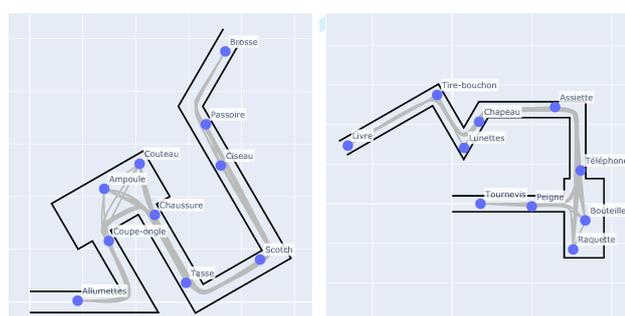
POI reconstruction: For each map, an arrangement of POIs was developed, resulting in 4 map scenarios. For each specific scenario, 10 object names (see Tab. 1) were assigned a defined spatial position on a map (*i.e.* a POI). Each POI-pair can be characterised by a *Euclidean distance* d_{eucl} and a *Navigation distance* d_{nav} separating the 2 points. While the Euclidean distance is straightforward to calculate, the navigation distance was determined using a custom MATLAB tool, which enabled the drawing of spline-interpolated curves between 2 POIs while avoiding walls. All paths associated with inter-POI navigation distances are shown in Fig. 1.

Tactile maps: To test hypothesis $H3$, two versions of each map were fabricated using two support types of differing spatial resolution: fine resolution 3D-printed (3D), and coarse resolution thermoformed swell touch paper (Thermo)². The low-definition Thermo map employed the same 2D design geometry but does not render fine resolution details or sharp edges. Their dimensions were identical (30 × 30 cm). Examples of the fabricated tactile maps are shown in Fig. 2.

2.2.3 POI-pair distance comparison task details: For each scenario and each subject, the object for the distance comparison task consisted of a selection of 20 pairs from all possible combinations of POIs for each scenario, evaluated twice using 2 repetition blocks. Pairs were formed based on a common first detail (*e.g.*, Lunette–scotch / Lunette–clavier) and a relation question for the participant to answer: “is shorter?” ($\overset{?}{<}$) or “is larger?” ($\overset{?}{>}$). Pairs for which $|d_{eucl} - d_{nav}| < \epsilon$ were excluded to ensure an undisputed correct/incorrect answer with respect to the employed perceptible. The ordering of all possible combinations was randomised and assigned to each subject based on their attributed number, with the following constraints :

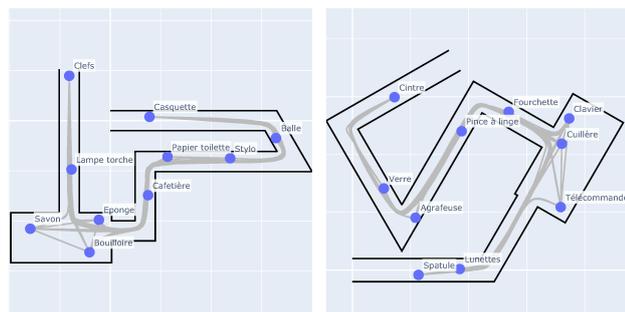
Table 1. Non-repeating names of POIs in each scenario (in French). An English translation is also provided.

Scenario 1		Scenario 2		Scenario 3		Scenario 4	
FR	ENG	FR	ENG	FR	ENG	FR	ENG
Allumettes	Matches	Assiette	Plate	Balle	Ball	Agrafeuse	Stapler
Ampoule	Light bulb	Bouteille	Bottle	Bouilloire	Kettle	Cintre	Hanger
Brosse	Brush	Chapeau	Hat	Cafetière	Coffee machine	Clavier	Keyboard
Chaussure	Shoe	Livre	Book	Casquette	Baseball cap	Cuillère	Spoon
Ciseau	Scissors	Lunettes	Glasses	Clefs	Keys	Fourchette	Fork
Coupe-ongle	Nail clipper	Peigne	Comb	Eponge	Sponge	Lunettes	Glasses
Couteau	Knife	Raquette	Racket	Lampe torche	Flashlight	Pince à linge	Peg
Passoire	Strainer	Téléphone	Telephone	Papier toilette	Toilet paper	Spatule	Spatula
Scotch	Tape	Tire-bouchon	Cork screw	Savon	Soap	Télécommande	Remote
Tasse	Cup	Tournevis	Screw driver	Stylo	Pen	Verre	Glass



(a) Scenario 1.

(b) Scenario 2.

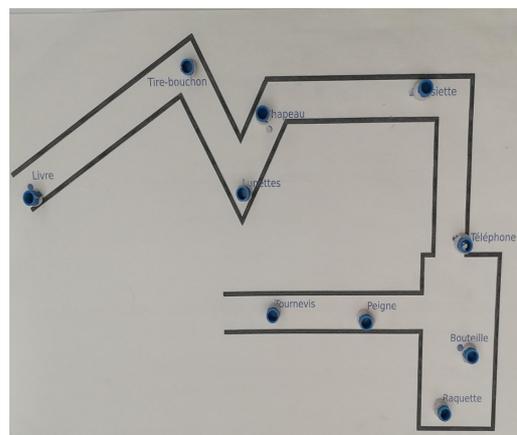


(c) Scenario 3.

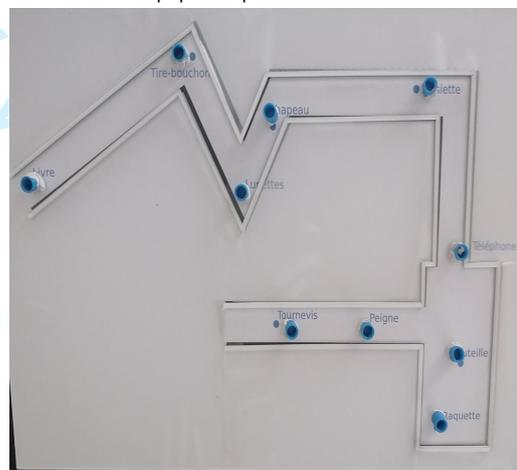
(d) Scenario 4.

Figure 1. The four proposed scenarios, including POI placements and all possible d_{nav} paths.

- The same distance does not appear in three successive comparisons.
- An equal number of $<$ and $>$ must appear within each repetition block.
- Assuming a given perspective, allocentric or egocentric, there should be an equal number of “true” and “false” correct responses within a repetition block.
- Assuming a given perspective, a maximum of 3 successive identical responses (a series of 3 “true” or 3 “false”) is permitted.
- The ordering of the N conditions is random and uncorrelated between repetition blocks.
- The presentation order of the 2 pairs remains the same over the 2 repetition blocks, while the comparison sign ($<$, $>$) is inverted. Hence, if the participant is consistent, the nature of the answer is opposite over



(a) Thermo swell touch paper map.



(b) 3D printed map.

Figure 2. Two example tactile map scenario reconstructions showing POI markers and associated labels, scenario 2, ID#018, group EB.

the two blocks (e.g. “false” in the first block and “true” in the second block).

2.3 Procedure

Participants were tested individually. The total duration of the experiment was ≈ 1.5 hr. Each participant first signed the consent form and completed an information sheet. They were then assigned 2 distinct scenarios among the existing 4,

1
2 which were presented on 2 different *support*; *i.e.* if the first
3 scenario was presented on a 3D-printed map, the second was
4 presented on swell touch paper, and vice-versa. POI positions
5 were fixed by temporary fixative paste for each scenario
6 and were indicated by visual points on the supports for the
7 experimenter.

8 **2.3.1 Procedural familiarisation phase:** To familiarise
9 participants with understanding the task (procedural learn-
10 ing), there was first a short phase of mental comparison
11 of distances between 6 cities located on the periphery
12 of the map of France (Strasbourg, Marseille, Perpignan,
13 Bordeaux, Cherbourg, Dunkerque). Participants had first to
14 remember their spatial locations, chosen so to be easy,
15 haptically exploring a relief map with 6 markers repre-
16 senting the different cities. Then, the participant had to
17 answer TRUE or FALSE to statements concerning the mental
18 comparison of distances, *e.g.* “Strasbourg–Marseille *bigger*
19 *than* Strasbourg–Dunkerque”. Participants had to mentally
20 imagine the distance between the first two cities mentioned
21 and then between the other two cities. Due to the lack of
22 obstacles, responses to this preliminary task are expected to
23 be equal, regardless of the perspective taken.

24 Participants responded to decide whether the statement
25 was true, indicating this by pressing a key on the computer
26 keyboard. To answer TRUE, they pressed the “L” key on the
27 keyboard (AZERTY) with their right hand; to answer FALSE
28 they pressed the “S” with their left hand. The two keys
29 were covered with felt fabric to facilitate key recognition and
30 finger placement. Following this evaluation, two participants
31 were eliminated due to their inability to pass the procedural
32 screening test.

33 **2.3.2 Exploration learning phase:** Participants first hap-
34 tically explored the scenario maps on the attributed *support*
35 without any landmark objects, and then, 10 markers (verbally
36 assigned names) were positioned at given POIs. After a
37 familiarisation exploration, in which participants were free
38 to take all the time needed to understand the map without
39 the objects (Afonso 2006; Boumenir 2011), participants
40 explored the first scenario (the map with the markers)
41 without time constraints. The markers were then removed,
42 and participants were asked to reconstruct the scenario for
43 the first time. The experimenter corrected placement errors
44 by taking the participant’s hand (holding the incorrectly
45 positioned counter) and directing it to its correct position
46 (as in previous studies with blind participants (Afonso 2006;
47 Afonso et al. 2010)). This procedure was repeated until
48 the participant felt they had memorised all the objects and
49 their correct locations, finalising the second reconstruction
50 task. The exploration time and the number of explorations
51 required by the participant to memorise each scenario were
52 recorded.

53 **2.3.3 Free recall task:** After learning the spatial configu-
54 ration of a scenario, participants were asked to count down
55 in steps of 3 from a random 3-digit number for 2 minutes
56 (interference task), and then perform the free recall of the
57 objects present (simple memory task). They could then
58 proceed to the mental comparison of distance tasks.

59 The number of objects correctly recalled by participants
60 was recorded as a score out of a possible 10.

2.3.4 Mental comparison of distance task: The admin-
istration of this task was automated (coded in Psychopy3,
version 2020.2.4 (Peirce et al. 2019)). All instructions were
given verbally by the computer program, either in the form
of recorded or computer-generated speech. All participants
accomplished the experiment on the same laptop (Acer, swift
5).

Participants were told that each trial would first consist
of hearing the names of two objects on the map. They were
invited to picture the entire map and then to focus on the
distances separating a pair of named objects (*e.g.* Lunette–
scotch). After a pause of 2 s, the “relation statement” was
presented, *i.e.* “plus petit que” (“smaller than”), or “plus
grand que” (“greater than”). After a pause of 2 s, the second
pair of named objects were presented (*e.g.* Lunette–clavier).
From the presentation of the second pair, participants were
invited to focus on the newly specified distance and compare
it with the first one. Participants had then to respond if the
relation statement was TRUE or FALSE, using the attributed
button (indicating if the statement between the distances of
the two proposed pairs was true or false). Responses and
response times were recorded. Participants were allowed to
take a short break between the 2 repetition blocks if desired.

The interpretation of the term “distance” was left to the
participants. Nothing in the experimental instructions was
included to influence this choice for the participants. They
were entirely free to resolve the task using an allocentric
or egocentric mental map for distance evaluations. Two
principal metrics were calculated based on the mental
distance comparison responses:

After completing the mental comparison of distance task,
participants were asked to make a final POI reconstruction of
the scenario.

Distance type agreement score: The total score of cor-
rect answers according to each of the two perspectives was
calculated. As the allocentric and egocentric interpretations
were always in opposition, the *distance type agreement*
score for allocentric representations (based on Euclidean
distances) is the complement of the *distance type agreement*
score for egocentric representations (based on navigation
distances). The predominant perspective (allocentric ver-
sus egocentric) used by each participant was computed by
analysing which perspective produced the highest number of
correct answers. From there, participants were categorised
as belonging to the egocentric or allocentric perspective for
each map studied.

Distance comparison grouping: We systematically tab-
ulated the number of correct answers (according to the
Euclidean versus Navigational distances) to obtain a score
out of a possible total of 40.

Distance comparisons were categorised into three cate-
gories (Small = $D1$, Medium = $D2$, Large = $D3$), depend-
ing on the magnitude of the difference between the two
POI-pairs (henceforth referred to as an *item*). Thresholds
were determined to generate subsets of approximately equal
distributions, given the actual distance distances employed
in the *POI-pair distance comparison task* for each item.
In the Euclidean condition, combining the 4 scenarios, $D1$
comprised 58 items ($\Delta d_{\text{eucl}} \leq 3.5$ cm on the tactile maps),
 $D2$ 50 items (3.5 cm $< \Delta d_{\text{eucl}} \leq 6.5$ cm), and $D3$ 52 items

($\Delta d_{\text{eucl}} > 6.5$ cm. In the navigation condition, combining the 4 scenarios, $D1$ comprised 46 items ($\Delta d_{\text{nav}} \leq 10$ cm), $D2$ 56 items ($10 \text{ cm} < \Delta d_{\text{nav}} \leq 18$ cm), and $D3$ 58 items ($\Delta d_{\text{nav}} > 18$ cm).

2.3.5 POI Reconstruction tasks: Participants placed the 10 physical markers on the original tactile map, initially devoid of markers, identifying each corresponding POI name. Reconstructions were photographed at the following three steps: first reconstruction attempt, final reconstruction at the end of the exploration learning phase, and finally, the reconstruction after the distance comparison task. An example of the map reconstruction photos taken at each stage is shown in Fig. 3.

The POI reconstruction photographs were analysed (Webplotdigitizer³) to extract the coordinates of the POIs placed by the participants. These 10 geometrically arranged reference points define a 2D landmark map. The two-dimensional regression, detailed in Sec. 2.2.1, first optimises scale and rotational alignment before comparing the geometrical structure similarity of each reconstructed landmark map to the scenario reference.

2.4 Participants

The experiment involved 39 participants aged 19 to 60 yrs ($M = 34.4$, $std = 13.5$). All participants were autonomous in their daily lives, which included many activities or hobbies, as assessed by their responses to a preliminary screening questionnaire. All were recruited in the Lyon area (France) through the *Institut de Formation en Masso-Kinésithérapie pour Déficients de la Vue* (IFMK DV), *Fédération des Aveugles et Amblyopes de France*, *Union Nationale des Aveugles et Déficients Visuels* and *Action Handicap France*, and were paid for their participation.

One group of participants was composed of 11 early blind individuals who had totally lost their sight before the age of 2.5 yr (3 male & 8 female; aged 30 to 55 yrs, $M = 44$, $std = 8$; group *EB*) due to either an incubator accident, craniostenosis, glaucoma, retinitis pigmentosa, genetic disease, retinal detachment, or some other unidentified origin. A second group was composed of 13 individuals with late-onset blindness (11 male & 1 female; aged 25 to 60 yrs, $M = 42$, $std = 12$; group *LB*), who had lost their sight between the age of 4.5–36 yr, due to retinal detachment, accident, disease, or genetic disease. A third group comprised 15 blindfolded-sighted individuals (7 male & 8 female; aged 20 to 51 yrs; group *BS*). All participants within the *BS* group had correct or corrected normal vision and wore blindfolds during the experiment, as in previous studies (Afonso 2006; Afonso et al. 2010; Grison and Afonso Jaco 2020).

To avoid any potential bias between groups *EB* and *LB* compared to *BS*, several data were collected about the participants, such as age, educational and sociocultural backgrounds, and information about their autonomy in their everyday life. At the outset of the study, the *BS* group was constructed to equally match the demographics of the *EB* and *LB* participant pool. Due to the COVID pandemic, however, several subjects recused themselves from participating due to the pandemic restrictions and

health concerns. The demographics remained comparable but not as ideally matched as at the outset.

Three *EB* and three *LB* were later excluded from the experiment, as they reported being unable to achieve the tasks and decided not to pursue the experiment after the first task. One *BS* was excluded due to the random nature of their answers.

3 Results

Analysis of variance (ANOVA) was carried out with independent variables: Group (*EB*, *LB*, *BS*) and Support (thermo swell touch paper = *T*, 3D printed = *3D*); design variables Scenario (1–4) and Distance (*D1*, *D2*, *D3*); and dependent variables (percentage of correct responses and response time). In the case of a significant effect of one of the independent variables or of their interactions (group \times distance, for example), this analysis was then followed by a posthoc analysis, a 2×2 multiple comparison test, the Scheffé *F*-test.

3.1 Map learning

Exploration times (map without or with POIs) and the number of explorations were measured during the learning phase. No significant differences were found between groups or between supports. Participants took significantly more time on average ($F(1, 71) = 4.06$, $p = 0.05$) to explore the map with POIs ($M = 1.43$ min) than without ($M = 1.17$ min).

3.2 Free recall task

In the free recall task, participants recalled 9–10 correct names. No significant differences were observed regarding support. Group factor analysis shows a significant difference ($F(2, 75) = 7.49$, $p = 0.001$) between *EB*, who recalled fewer names on average (9.30), than *LB* (9.92) or *BS* (9.90). No significant differences were observed between the average number of names recalled by *LB* compared to *BS*.

3.3 Mental exploration method

In analysing results, while no explicit instruction was given, it was assumed that participants employed either an egocentric (Navigation distances) or allocentric (Euclidean distances) frame of reference consistently. The *distance type agreement score* was tabulated for each participant (*EB*, *LB*, or *BS*) and each support (*T* or *3D*), being the number of correct responses obtained from an allocentric perspective (Euclidean type map) or egocentric one (Navigation type map). We discarded from this analysis those participants whose scores were 45–55% as inconclusive/inconsistent, eliminating participants whose responses were close to random between the two perspectives. This could be due to a poor capability with the distance comparison task or the presence of dynamic switching between perspectives during the study, both of which render results unusable in the current analysis. This selection analysis resulted in retaining 89% of the initial participants: 8 *EB*, 13 *LB*, and 15 *BS*. Moreover, this first analysis allowed us to add the variable “perspective” ($P = \text{egocentric or allocentric}$) to the analyses.

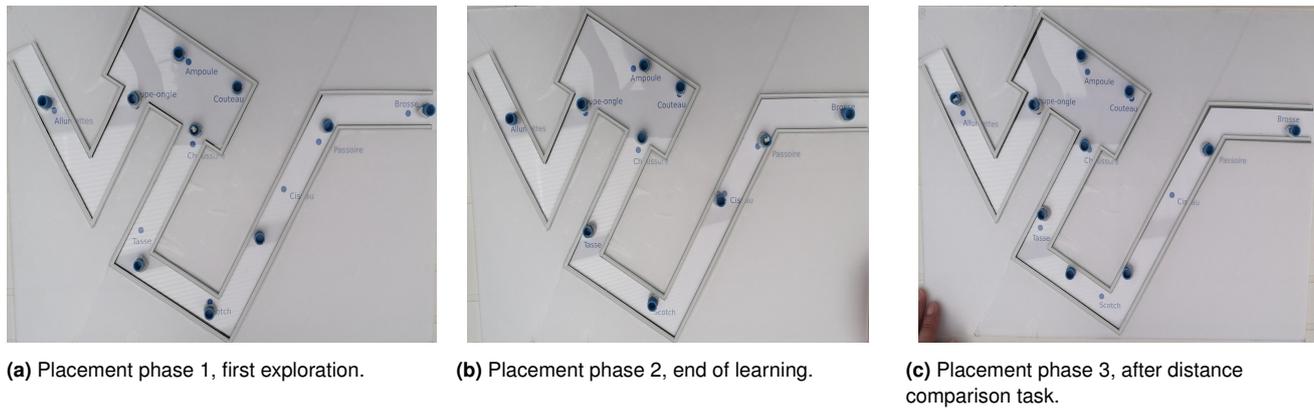


Figure 3. Example overhead photo series of map reconstructions, scenario 1, ID#018, group *EB*.

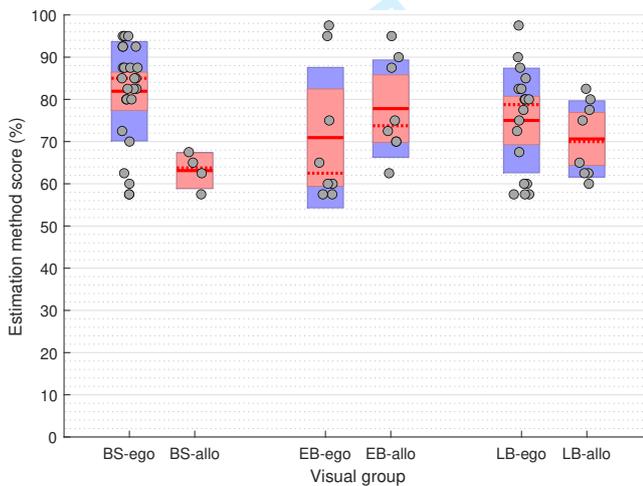


Figure 4. Frequency of use of distance estimation methods according to visual condition and perspective grouping. Plot shows median (red line), mean (dashed red line), 95% confidence interval (orange area), 1 standard deviation (blue area), as well as the full data scatter plot.

The first global analysis was to observe which perspective participants used to resolve the experimental task, with a summary shown in Fig. 4. These data, and subsequent plots, employing 95% confidence interval reporting, as promoted in various statistical literature (Cumming 2014; Baguley 2009), allows for a rapid visual comparison of significance as well as an indication of the effect size. Those who benefited from early visual experience (BS and LB) used mostly an egocentric perspective to solve the task of mental comparison of distance (correct answers respectively mean 87% of the cases for the BS, and 69% of the cases for the LB), independent of the support. In the case of participants without early visual experience, results differed according to support. *EB* in condition *T* responses were correct for an allocentric perspective in 62.5% of the cases (or 5 out of 8 participants), while the opposite was observed in condition *3D*, with 62.5% of participants responses being in accordance with an egocentric perspective.

Examining the consistency of responses at the group level, we evaluated the percentage of times they actually used this perspective compared to chance. Thus, the higher the percentage of coherence of a group, the more the use of one or the other perspectives was preferred. Conversely, if the

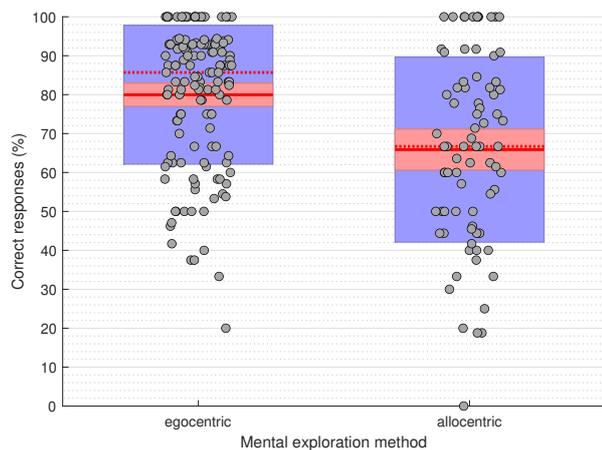
result is close to 50%, it indicates a chance response. The statistical analysis shows a significant interaction between group and perspective ($F(2, 60) = 3.80, p = 0.02$). More precisely, results show that for *BS-ego* using egocentric perspective, the frequency of responses corresponding to their method (*i.e.*, egocentric) is significantly higher (82%) than *BS-allo* using the allocentric perspective (63%; $p = 0.006$). Another interesting result shows that the consistency using an egocentric perspective to achieve the task, although high for both, is significantly different ($p = 0.03$) between *EB-ego* (71%) and *BS-ego* (82%). For blind groups, in contrast, there was no significant difference observed with either method for *EB* (*EB-allo*: 78%; *EB-ego*: 71%) or *LB* (*LB-allo*: 71%; *LB-ego*: 75%).

3.4 Mental comparison of distances task

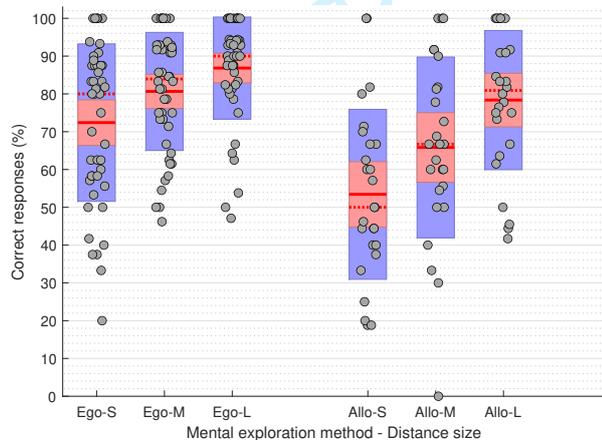
3.4.1 Percentage of correct responses Results showed no observable effect of Group or Support on the percentage of correct responses (to the assigned *Perspective* of a given participant following individual distance type agreement scores). In contrast, analysis of the *Perspective* factor shows (see Fig. 5a) that participants using the egocentric perspective obtain significantly more correct responses than participants using the allocentric perspective ($F(1, 60) = 8.63, p = 0.005$). A post-hoc test showed these results had a Cohen's $d = 0.70$, indicating a medium to large effect size. It is noted that the mean value falls outside the 95% CI range, indicating a lack of normality in the responses. This is due to the saturation effect of 100% correct responses on the data distribution, which is more prevalent with the egocentric group's results than those of the allocentric group.

Regardless of the perspective used during the task, the results also show a *Distance* effect, showing that Small, Medium and Large differences in distance were treated significantly differently ($p \leq 0.001$) from each other ($F(2, 12) = 34.45, p < 0.001$). Thus, the more the difference between two distances is, the higher the percentage of correct responses.

Results also indicate a significant interaction between the *Perspective* and *Distance* variables ($F(2, 120) = 4.48, p = 0.013$), as seen in Fig. 5b. The percentage of correct responses is higher when participants take an egocentric rather than an allocentric perspective to solve the task, regardless of the type of distance differences (Small,



(a) Percentage of correct answers according to the perspective group attribution (showing results for all distance differences (Small, Medium, and Large)).

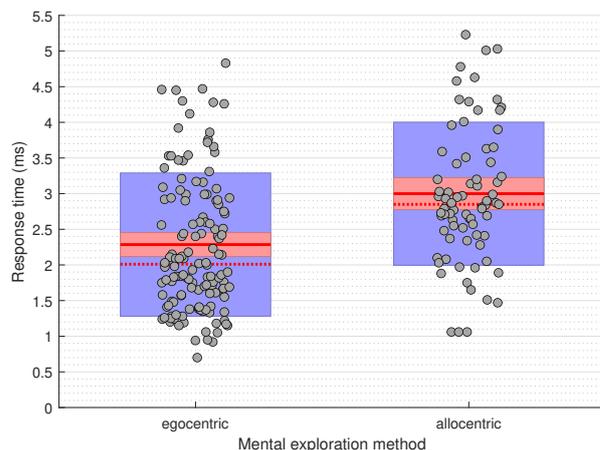


(b) Percentage of correct answers according to distance difference (Small, Medium, and Large) and perspective group attribution.

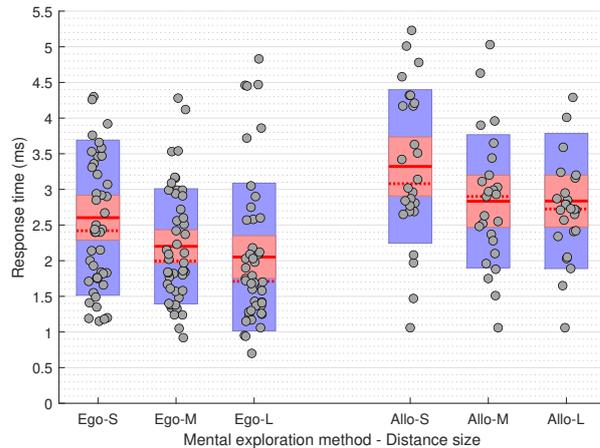
Figure 5. Percentage of correct answers. (See Fig. 4 for plot style legend.)

Medium, or Large). The post-hoc analysis shows that in the case of an egocentric perspective, only the difference between the Small and the Large distances appears significant ($p < 0.001$). However, when participants used an allocentric perspective, we find what has been shown in previous studies (Afonso 2006; Noordzij et al. 2006; Picinali et al. 2014), namely that the Small distance differences are treated differently from the Medium ($p = 0.05$) and the Large ($p \approx 0$); and that the Mediums are also treated differently from the Largest ($p < 0.05$); thus, the more the difference between two distances is, the higher the percentage of correct responses.

3.4.2 Response time Analysis of response times of correct responses shows a significant effect of the Perspective variable ($F(1, 59) = 9.42$; $p = 0.003$), see Fig. 6a. Participants classified as using the allocentric perspective took significantly longer to respond than egocentric perspective participants ($p = 0.001$). A post-hoc test showed these results had a Cohen's $d = 0.71$, indicating a medium to large effect size. As the mean value is outside the median, this indicates a lack of normal distribution. Analysing response times on a log scale corrects this effect, resulting in Cohen's $d = 0.75$. Secondly, results show a



(a) Correct response times according to the perspective group attribution.



(b) Correct response times depending on distance difference (Small, Medium, and Large) and perspective group attribution.

Figure 6. Response times. (See Fig. 4 for plot style legend.)

significant effect of the Distance variable ($F(2, 12) = 12.03$; $p < 0.001$). Thus, small differences in distance imply a significantly longer processing time than either medium ($D1$ and $D2$; $p < 0.001$) or large ($D1$ and $D3$; $p < 0.001$) differences in distance, see Fig. 6b.

3.5 POI reconstruction

Results showed no observable Scenario, Group, or Support effect on the reconstruction coherence relative to the prescribed POI placements. As shown in Fig. 7, overall values for bidimensional regression analysis are quite high, indicating good map reconstructions in all conditions. Differential analysis of the three POI placement tasks ($F(2, 12) = 8.59$, $p < 0.001$) revealed more accurate placement at the end of learning (placement phase 2) than at the first exploration (placement phase 1; $p = 0.012$), indicating participants were well prepared for the distance comparison tasks. After solving the mental distance comparison tasks, results at phase 3 show a slight decrease relative to phase 2, but still generally higher than at phase 1, though there are a few major outliers, likely due to test fatigue in participants. As the instances of outliers are quite limited and do not appear to affect the statistical results of the groups (as seen in Fig. 7), no further treatment of these few outliers is considered necessary.

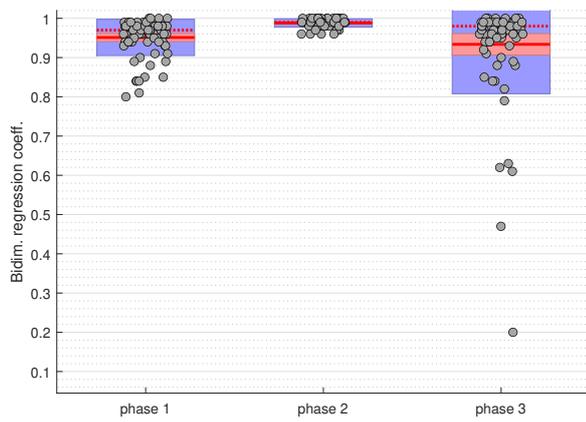


Figure 7. Bidimensional regression analysis across (scenario, group, support) for the placement phases. (See Fig. 4 for plot style legend.)

4 Discussion

This study investigated the type of spatial mental representations constructed from two different haptic modalities, depending on participants' visual conditions. We designed a protocol that allowed participants to choose their method of mental exploration without any explicit instructions on how to explore the spatial representation they encoded during the learning phase. We used the distance comparison task designed by Denis and Zimmere (1992) to assess the ability to construct spatial mental representations and measure their properties.

Our hypothesis suggested that the preference for an egocentric versus allocentric perspective when exploring mental maps is influenced by prior visual experience (early blind = *EB*, late blind = *LB*, no visual deficit (blindfolded-sighted) = *BS*). Previous studies have shown performance advantages in mental comparison of distance tasks between perspectives regarding visual experience (allocentric for *BS*, egocentric for *LB* and *EB* (Péruch et al. 2006; Noordzij et al. 2006)). Using the same task in an experiment that allowed each participant to choose their perspective freely, we expected participants' choices to be consistent with those findings. We did not anticipate any performance advantage between perspectives (allocentric versus egocentric) when participants were allowed to choose their perspectives freely.

Limitations

Several assumptions were made when designing the protocol and analysing the results. Results are therefore to be considered in light of these limitations.

Firstly, we have controlled the information provided and the size of the environment, both of which are typical of indoor navigation by visually impaired subjects (typical tactile map, typical corridor size). We examined what strategies were employed and to what degree they were common according to visual experience when removing the instructional bias observed in previous studies. Such analysis excludes consideration of prior training by each individual participant and other elements beyond our control. Consequently, we include in **H1** the supposition that these group definitions have experienced common learning strategies, thereby controlling for this factor by group.

Secondly, selected participants were autonomous in their daily lives (not institutionalised, etc.), had a profession, or were involved in associations. They were considered similar enough in demographic conditions to construct groups according to their degree of visual deprivation. As individual differences could not be controlled, participants were screened to ensure that at least they understood the basic task through a procedural familiarisation phase, which only eliminated 2 potential participants.

Finally, the procedural screening in the familiarisation phase involved simple distance comparisons of points situated on the perimeter of a map of France. While answers to this task are expected to be the same for both allocentric and egocentric perspectives, due to the absence of obstacles, some potential bias in the choice of perspective could be considered from this prior task. Classification results for the taken perspective based on responses to the largest distance difference comparison allowed for a clear classification of 89% of participants, with the remaining participants potentially either performing more errors or being inconsistent with the perspective employed. From those clearly classified, accuracy rates were 80% on average for all distance comparisons. These results provide a strong indication of the consistency of the employed strategy in general, and the evidence of the two perspective classifications suggests that the effect of prior task exposure was limited or absent.

H1: Preference for egocentric perspective in individuals with early blindness

Regarding the subjectively chosen method, blindfolded-sighted subjects significantly preferred the egocentric method. Unexpectedly, we observed no marked preference for one method over the other between the two blind groups. Therefore, the experimental results do not align with hypothesis **H1**; rather, they reveal no marked preference for one method over the other in blind groups. These results question the findings of the literature, which indicate that the absence of early visual experience overwhelmingly favours the use of an egocentric representation (Millar 1994; Noordzij et al. 2006). Without specific instructions on the type of perspective to use, early blind individuals did not systematically employ an egocentric navigation perspective. This strongly suggests that experimental instructions may have influenced previous studies.

H2: No performance advantage for either perspective

Concerning the two types of mental exploration methods, our experiment highlighted significant differences irrespective of the visual experience group. The outcome of this study does not corroborate hypothesis **H2**. Instead, it indicates that using an egocentric perspective led to better performance (faster and more correct answers).

H3: Support material effects performance

Hypothesis **H3** was not confirmed, with the results of this study indicating that regardless of the type of support explored (3D printed or thermoformed), participants could

memorise many items based on information derived from tactile exploration of the environment. We note, however, that both maps contained the same geometrical information and symbols (POI markers). For more complex maps, multiple abstract symbols could be more complicated in initial explorations for untrained people and even regular users. Therefore, we can assume the effect of the type of POI symbols could explain our divergent results with prior research (Bleau et al. 2023). Adapting our study to more complex maps with 3D contexts/requirements may bring out significantly different results in mental representation abilities between the two types of maps.

Conclusion

In all groups, participants demonstrated the ability to elaborate reliable mental representations, and the results reproduced the symbolic distance effect described in the literature, where larger differences between two distances resulted in shorter response times and a higher percentage of correct responses (Afonso 2006; Noordzij et al. 2006; Picinali et al. 2014).

Given the difficulty of the task and the haptic modality (processing information item by item), we can suggest that using an egocentric perspective was easier and more efficient regardless of visual experience. Participants achieved better results using the mental exploration method that did not require transposing information into verbal or visuospatial format, which questions the Baddeley and Hitch (1974) model that considers the working memory system based on those two modalities. Participants could directly encode information from tactile exploration to construct a reliable representation and use it in our distance comparison task by exploring in a navigational way, item by item, without transposing it into verbal or visuospatial information. Our results highlight the limitations of that model, as raised previously in Grison and Afonso-Jaco (2020), suggesting that participants relied directly on sensory-motor information to construct their spatial models. These findings support the existence of different working memory systems, as proposed by Cowan (1988), which define a format based on multiple sensory systems (modality-specific components of memory in the first phase, interactions between modalities in the second phase).

Interestingly, it was observed that most blindfolded-sighted participants did not necessarily transpose tactile information into a visuospatial format to construct their representations, even though using tactile maps was unusual. Despite previous studies identifying good abilities for blindfolded-sighted participants to use allocentric representations, they spontaneously relied on egocentric representation, probably induced by the tactile exploration imposed in our study. However, these findings did not appear significant for the blind participant groups. Many blind participants indicated in the pre-test questionnaire that they had learned how to explore tactile maps in school or during their locomotion training. This learning effect could explain why they randomly used one representation or the other, as they were accustomed to switching from one model to another.

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Declaration of conflicting interests

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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Annex: Mental exploration and the symbolic distance effect

One widely employed paradigm that has been developed to evaluate spatial mental maps has been the mental scanning task, originally proposed by [Kosslyn et al. \(1978\)](#) and later adapted to studies examining various learning protocols with both sighted and blind individuals.

In the mental scanning task, the participant is first asked to learn the spatial configuration of an obstruction-less environment, with different objects located around its perimeter, whether it is a “classic” island ([Kosslyn et al. 1978](#)) or a simplified island in the shape of a circle ([Denis and Cocude 1992](#)). Participants are then asked to imagine an object moving in a straight line, at a constant speed, between different objects (in pairs) that were part of the initial configuration they had learned.

The most notable result obtained from mental scanning tasks consisted in the observation of a linear relationship between the mental travel time between two points and the physical distance between them; thus, the longer the distance to be covered between two points, the longer the time required for its mental travel, given the aforementioned instructions ([Beech 1979a,b, 1980](#); [Borst and Kosslyn 2008](#); [Borst et al. 2006](#); [Dror et al. 1993](#); [Iachini and Giusberti 2004](#); [Kosslyn et al. 1978](#); [Pinker et al. 1984](#)). This

time/distance correlation was analysed as evidence that the metric properties of the initial environments were preserved in the mental representation elaborated by the individuals.

The next question was whether this feature of mental representations, found in psycho-physics and commonly referred to as the “symbolic distance” effect in the case of mental representations ([Moyer 1973](#); [Paivio 1975](#)), arose solely from the fact that the studies were conducted using visually perceived images ([Kosslyn 1973](#); [Kosslyn et al. 1978](#)) from which individuals had to create a mental representation. Alternatively, would it be observed whatever the initial support? Thus, distance mental exploration paradigms have been employed after learning by verbal description ([Denis and Cocude 1989, 1992, 1997](#)), haptic exploration ([Kerr 1983](#); [Röder and Rösler 1998](#)), locomotor exploration in real and/or virtual environments ([Afonso et al. 2003](#); [Afonso 2006](#); [Iachini and Giusberti 2004](#); [Picinali et al. 2014](#)). These studies have highlighted the preservation of the symbolic distance effect.

Investigating the influence of vision on the characteristics of mental representations, Afonso et al. ([Afonso 2006](#); [Afonso et al. 2010](#)) proposed a task, adapting that of [Denis and Cocude \(1992\)](#), to participants who were blind from birth, late-blind, and blindfolded-sighted, to evaluate the influence of early visual experience in the results obtained previously. Participants were asked to solve a mental scanning task after learning the spatial configuration of an environment by either verbal description or haptic exploration. While the time-distance correlation was clearly observed for participants with visual experience, it was completely absent for participants who were blind from birth. On the other hand, as soon as the participants who were blind from birth were immersed in a full-scale virtual reality representation of the environment (and no longer exploring in a manipulative space, *i.e.* map), the results obtained in the mental scanning task, whether after a verbal description or a motor exploration of the environment, showed a strong positive correlation between the mental navigation time and the distance to be covered.