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# The dynamic process of cognitive mapping in the absence of visual cues: human data compared with animal studies

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## SUMMARY

**The present study aimed to investigate the behavior involved in constructing spatial representation in humans. For this, blindfolded adult human subjects were introduced into an unfamiliar environment, where they were requested to move incessantly for 10 min. Analysis of the locomotor activity of the participants revealed the following exploratory behaviors: (1) 'looping'; (2) 'wall-following'; (3) 'step-counting'; (4) 'cross-cutting'; and (5) 'free traveling'. Looping is a typical exploratory mode of sightless explorers, based on returning to a recently traveled place. Wall-following is common in enclosed spaces, whereby explorers follow the perimeter of the environment. Both looping and wall-following are based on an egocentric frame of reference by which explorers obtain information about the shape, size and landmarks in the environment. Blindfolded explorers displayed step-counting in order to scale the environment and the relationships in it. Altogether, exploration by looping, wall-following and step-counting resulted in an allocentric spatial representation. The acquisition of spatial representation was manifested by cross-cutting and free travel, with subjects walking in a relatively fast and decisive manner. In light of the above modes of activity, we suggest that exploration of an unfamiliar environment is a synergetic self-organized process (synergetic inter-representation networks, SIRN model); an interplay between external and internal representations. According to this model, the interplay gives rise to an order parameter, such as the environment's dimensions or geometry, enabling progression to a subsequent exploratory behavior. This dynamic and sequential interplay reaches a steady state when a spatial representation (i.e. 'cognitive map') is established.**

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Key words: exploration, cognitive map, egocentric reference, allocentric reference.

## INTRODUCTION

The notion that humans and animals form a representation of their surrounding environment as a form of 'cognitive-like map' was raised by Tolman (Tolman, 1948), based on spatial problem-solving tasks in rats. This notion attracted further attention with the discovery of 'place cells' that are associated with spatial information processing in the hippocampus (O'Keefe and Nadel, 1978). According to O'Keefe and Nadel, an internal representation of a new environment is established in the hippocampus during exploration (O'Keefe and Nadel, 1978). The environmental properties utilized in the construction of such an internal representation were suggested to be, for example, the geometric relationships between landmarks (Cheng, 1986), the principle axes of the environment (Gallistel, 1990) or integration of positional and directional cues in the environment (Jacobs and Schenk, 2003). These examples reflect the view that external properties of the environment shape the internal representation. Haken and Portugali (Haken and Portugali, 1996) suggested a theoretical model that views cognitive mapping as a dynamic process of integrating internal and external representations, a model termed 'synergetic inter-representation networks' (SIRN). Obvious cases that demonstrate this interplay between internal and external images are those of animals constructing their living space, such as mole rats when digging their burrow system (Zuri and Terkel, 1996), and spiders when spinning their web (Eberhard, 1990). Furthermore, the interplay between the internal and external image is reflected in behavior, as described for humans by Wise (Wise, 2000):

> "*It (space) is marked physically, with objects forming borders, walls and fences. The marker (wall, road, line, border, post, and sign) is static, dull, and cold. But space is marked, and shaped, in other ways as well. When lived (encountered, manipulated, touched, voiced, glanced at) it radiates a milieu, a field of force, a shape of space.*"

In accordance with the notion of a dynamic interaction between internal and external representations, and specifically the SIRN model (Haken and Portugali, 1996), our working hypothesis was that the spatial behavior of blindfolded human subjects introduced into an unfamiliar environment would reflect a dynamic and integrative process of constructing cognitive representation.

Our rationale for studying unsighted humans lay in the need to prevent stationary visual exploration and enforce motor exploration, whose paths of locomotion are measurable. Moreover, the paths of blindfolded individuals may resemble sighted exploration in a large-scale environment, where the whole surrounding is not visible and is therefore explored part by part. The advantage of analyzing routes of progression in humans lies in the ability to infer from their routes modes of exploration in a method comparable to that of animal studies (e.g. Drai and Golani, 2001; Young et al., 2007). Human subjects can also be interrogated regarding the modes of exploration that they used and asked to provide a sketch of the explored environment. For this study, therefore, we posed the following questions: (1) what behavioral patterns are utilized by blindfolded subjects in exploring an unfamiliar environment; (2) is there a typical order in which particular behavioral patterns unfold during exploration; (3) what demarcates the acquisition of spatial representation; and (4) is there a dynamic interplay between the physical environment and the behavior of the explorers in the course of cognitive mapping?

## MATERIALS AND METHODS

### Study subjects

Five male and five female biology students, 23–29 years old, voluntarily participated in the present study, after signing an informed consent document. The study was carried out under a permit from the Institutional Helsinki Committee for Human Experimentation.

### Apparatus

Subjects were tested in an unfamiliar empty room (3.5 m×10 m). The experimentation room was an underground war shelter, a compulsory space in Israeli buildings, with 30 cm thick cement walls and heavy metal doors, and without windows. The room was empty and quiet and unfamiliar to the students, located away from the laboratory and classrooms floors. During testing, the room entrance was covered with a curtain. Another, locked, door was situated near the center of one of the longer walls. Chalk lines were drawn on the floor, dividing the room into 48 areas of 80 cm×80 cm, selected because this distance is beyond the reaching distance of an average human subject. For example, an individual standing within a perimeter area of 80 cm×80 cm could touch the wall, but standing more than 80 cm from the wall would place the individual in another zone outside the perimeter. Each area was individually marked to identify the location of the tested subject.

### Procedure

Each subject was tested individually, without interaction with other participants. All subjects were informed before testing that they were participating in a study on exploring an unfamiliar environment. Testing began in an adjacent room to the test room, where the subject's eyes were covered with a blindfold. The subject was then led blindfolded into the test area. All subjects were positioned at the same starting point in the center of the room (away from the walls) and were asked to disorient themselves by three rotations on the spot, and then to move unrestrictedly and incessantly for 10 min and not to exit through the curtained door. Each subject's behavior was video recorded onto a camcorder (Sony DCR-HC85E, Tokyo, Japan) throughout testing by the experimenter who quietly followed her/him. After 10 min of locomotion in the room, the subject was led blindfolded out of the test area. The blindfold was removed and the subject was requested to fill out a questionnaire (see Appendix) that comprised three open questions and 10 ranking questions on a 5-rank scale.

### Data acquisition and analysis

Behaviors were scored during playback of the video files. Subjects' location and timing at each of the 48 zones were scored by means of software for behavioral analysis (The Observer, Noldus Information Technology, Wageningen, The Netherlands). Data files were then exported to Microsoft Excel for further analyses. Plots of the routes traveled by the subjects were reconstructed from ($X$, $Y$) coordinates over time. Data were found to be normally distributed by means of Kolmogorov–Smirnov and Lilliefors tests. Overall activity in the testing room was compared by one-way ANOVA. Gender difference was compared by means of Student's $t$-test. Travel velocity during the course of testing was compared by means of Pearson's correlation.

## RESULTS

### Subjects' description of their exploration in the test environment

In the questionnaire that the subjects filled out after the test, all 10 subjects correctly described the shape of the environment as a rectangular room. One did not specifically write 'rectangular', but sketched the shape of a rectangle. Four subjects (two female and two male) correctly estimated the size of the room in terms of the number of steps or meters. Nine subjects (five female and four male) explicitly mentioned using wall-following in their travel. Finally, all subjects reported that the layout of the environment was apparent to them by the end of the test.

When asked to present the method by which they had explored the environment, subjects generally described three exploratory means: (1) wall-following; (2) calibrating the environment; and (3) free traveling (crossing from wall to wall). Indeed, eight subjects (four females and four males) wrote that when the test began they first followed the walls. Seven subjects (three female and four male) reported that they counted steps in order to estimate the environment size, and six subjects (four female and two male) reported that over the course of the test they began to travel freely throughout the room. One female was exceptional in reporting that she first walked randomly and subsequently followed the wall; as were two male subjects, who gave only a brief report, mentioning only counting steps or wall-following as exploration methods. Finally, eight subjects plotted all landmarks (i.e. curtain and door) in their sketch, one female subject did not provide a sketch of the room but described in words the location of the landmarks, and one female subject neither sketched nor described the landmarks, but did estimate the exact shape and size of the room. Interestingly, although the subjects were aware of the landmarks and their location within the room, none mentioned them as a means of orientation.

All subjects wrote that they 'greatly' or 'very greatly' used the walls (wall-following) for planning their travel in the environment. Only one male subject wrote that the start point had 'some importance', whereas the other nine subjects wrote that it had 'no importance' or 'just a minor importance' for traveling in the environment. Finally, eight subjects (four female and four male) reported acquiring 'very good' or 'excellent' familiarity with the environment, while the other two (one female and one male) reported only a 'certain' familiarity. The above reports do not reveal any gender bias.

### Objective description of subjects' exploration from the video recordings

The area covered during testing did not differ among subjects (one-way ANOVA, $F_{1,8}$=0.79; $P$=0.399). In comparing the amount of locomotion near the walls of the test room with respect to other areas of the room, all subjects traveled more near the walls (one-way ANOVA, $F_{1,8}$=109.95; $P$<0.0001). The trajectories of locomotion of one female subject (Fig. 1) illustrate four spatial behaviors that outline the exploration of the subjects in the unfamiliar test environment. When the subject began traveling, she progressed counterclockwise closing a loop at the start point after 31 s (Fig. 1A). Notably, during looping she arrived twice at the room walls (the extreme left and right walls), but abandoned them instantly (after 5 s). After looping, she followed the walls, encompassing the entire

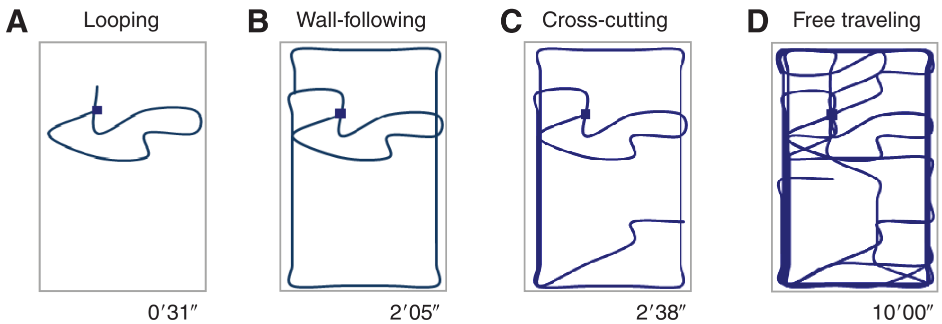


Fig. 1. Paths of progression (depicted cumulatively) of a blindfolded female subject (F7) in an unfamiliar environment. Four exploratory behaviors are represented from left to right. The end time of each phase is depicted at the bottom of each plot. The start point of testing is marked by the filled square.

perimeter (Fig. 1B). Having completed the first episode of perimeter traveling, she performed a cross-cut between near sectors of a corner (Fig. 1C), and subsequently traveled freely across the test room with numerous cross-cutting between adjacent and remote wall sectors (Fig. 1D).

Fig. 2 depicts the paths of locomotion of all 10 subjects based on the outline of the behaviors shown in Fig. 1. As shown, progressing along the walls of the room, which was reported by all subjects, was apparent in the paths of all of them ('wall-following', Fig. 2). This common behavior was either the initial exploratory behavior (F5, F8, M9, M10) or was preceded by other initial behaviors of familiarization, such as looping (F2, F7) or partial wall-following (M1, M3, M4). In the first minute of exposure to the unfamiliar room, two subjects displayed looping; that is, traveling in a circular path that closed at the path origin. Looping was apparent as these subjects did not cling to the walls like the other subjects; rather, they abandoned the walls and traveled back to the origin of their path, as typically seen in looping. In partial wall-following, subjects traveled along limited sectors of all four walls and only then proceeded to circle the entire perimeter. Another subject (F6) began her exploration with an unusual movement that she reported as 'random walk'. Indeed, in the first third of the test she repeatedly walked back and forth between the walls. Overall, circling the entire perimeter lasted typically 1–1.5 min for all subjects.

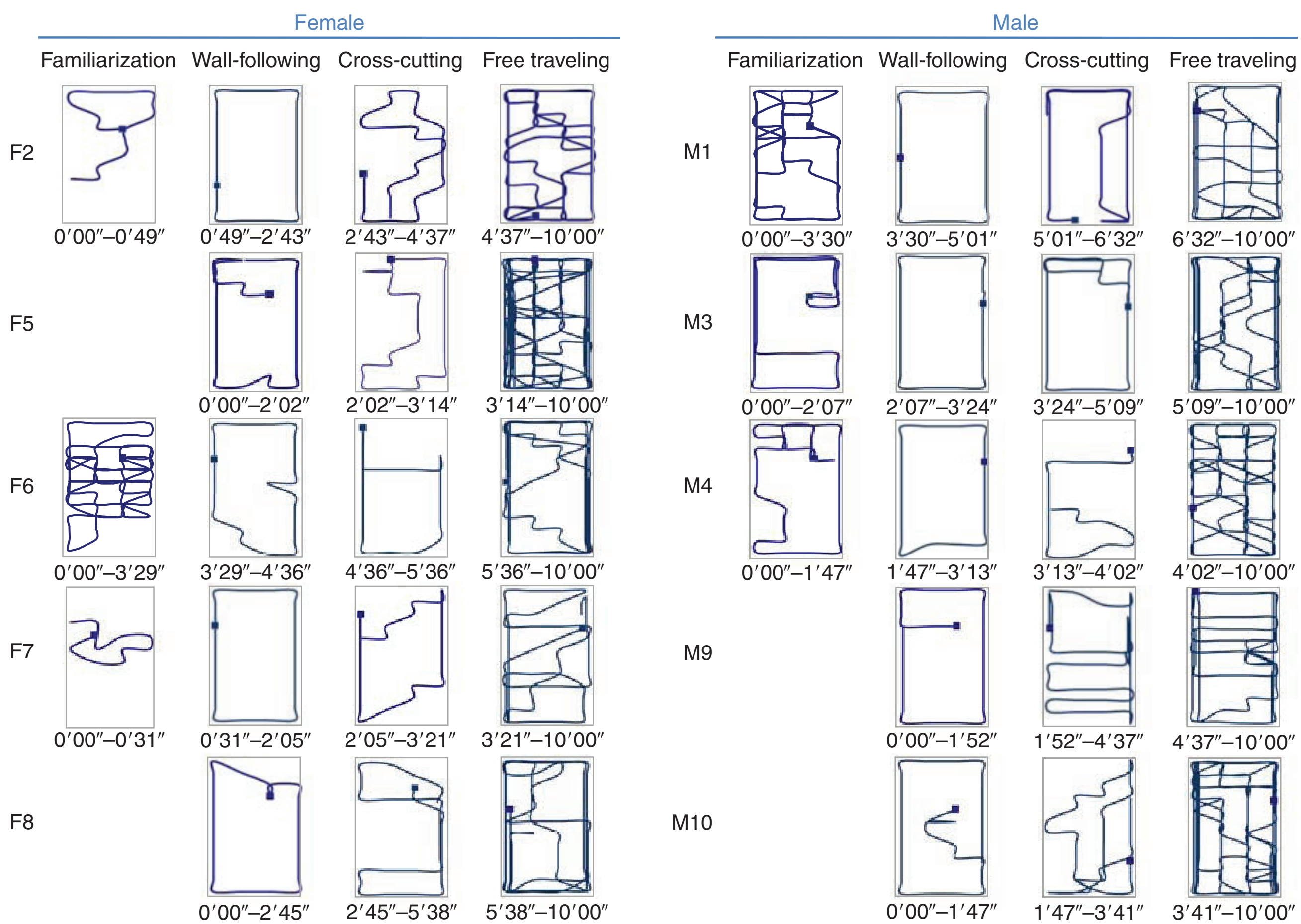


Fig. 2. Paths of progression of five female (left) and five male (right) blindfolded subjects in four modes of traveling. The first exploration phase of familiarization was characterized by looping (F2, F7), partial wall-following (M1, M3, M4) or random walking (F6). The start and end time of each phase is depicted at the bottom of each plot. The start of the path of progression in each phase is marked by the filled square.

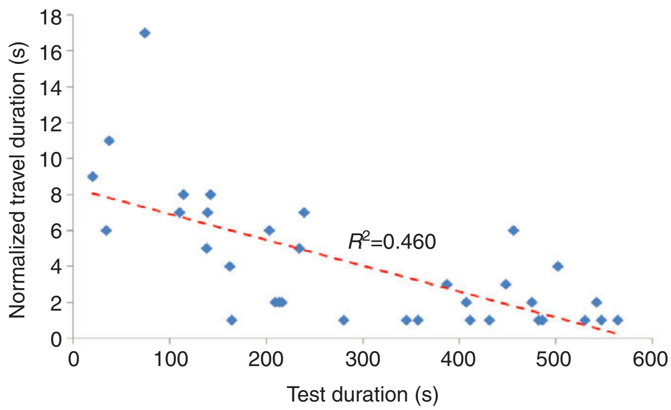


Fig. 3. The decrease in the duration of travel along similar path segments in time intervals across the 10 min of observation. Data points ($N$=34) represent all the path segments analyzed for the 10 tested subjects. For each individual, data were normalized as follows: the shortest duration of traveling a certain fixed path was defined as 1, and the duration in repeated travels of the same segment was scored by the additive value compared with that minimum. These additive values ($Y$-axis) are depicted according to their occurrence during the 600 s of observation ($X$-axis). Dashed line depicts the significant negative correlation.

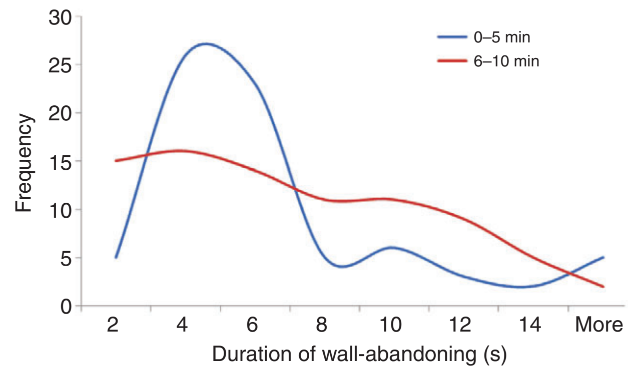


Fig. 4. The frequency of the duration of wall-abandoning in the first half (0–5 min) compared with the second half (6–10 min) of observation. As shown, the frequency of relatively short wall-abandoning was high in the first 5 min, whereas in the second 5 min there was an increase in the incidence of longer wall-abandoning.

The emergence of cross-cutting towards the opposite wall through the center (Fig. 2) denotes the transition to a new mode of traveling. The first cross-cut was distinct in being directed toward a wall, whereas previous occurrences of traveling through the center were either looping back to the start point or wandering about and bumping into walls (see supplementary material Movie 1). After the first occurrence of a cross-cut, subjects traveled freely, adjusting their cross-cuts when approaching a wall in order to avoid bumping into it (supplementary material Movie 1). The first cross-cut thus demarcated the beginning of a new behavioral phase of free traveling (Fig. 2). During free traveling, subjects frequently performed cross-cuts and abandoned the walls for longer periods. Also, subjects moved along a variety of paths and seemed to gain familiarity with the test environment to a level that allowed one subject to blindly dance his way through the room, and another one to take a brief backward walk.

As described above, seven subjects (three female and four male) reported step-counting during exploration. While this action could not be manifested in the trajectories of locomotion, it was discernible in the video recordings of eight subjects. In these subjects, intervals of step-counting always commenced in a typical start posture: the subjects stood with their back to the wall and one or two hands stretched backwards to touch the wall (see supplementary material Movie 1). From this initial posture, the subjects began to walk forward at a steady pace until reaching the opposite wall.

The above behavioral changes in the course of the 10 min of testing were also reflected in an increasingly faster traveling velocity. To demonstrate this, we measured in each subject the duration of repeated travel along the same path segment (e.g. from corner to corner along the wall). Because we measured duration for the same path segment at different time intervals, a presumed decrease in the duration of travel could indicate an increased travel velocity. Given that individual subjects used a different range of travel velocities and repeatedly traveled along different paths, data were normalized in relation to the shortest travel duration (in seconds), which was taken to be constant at 1. Accordingly, if a subject traveled a segment at intervals of 9, 10 and 11 s and another subject traveled at intervals of 19, 20 and 21 s, the sequence in each of these subjects was transformed to 1, 2 and 3. As shown in Fig. 3, there was a significant negative correlation ($R$=–0.68; $P$<0.05) between the duration of travel and the time of observation, indicating that travel velocity had increased in the course of the 10 min observation. This increase in traveling velocity was also confirmed separately in females and males ($R$=–0.45 and $R$=–0.14, respectively; $P$<0.05).

The emergence of cross-cutting and the subsequent free traveling involved an increased incidence of bouts in which subjects abandoned the wall. Whereas during the first 5 min of the test (first half of the observation) wall-abandoning was predominately short, in the last 5 min (second half of the observation) the incidences of longer wall-abandoning increased, along with a decrease in the incidence of shorter wall-abandoning (Fig. 4).

No gender differences were found in the parameters tested in this study. In the self-report provided by the subjects after testing, there was no difference between female and male descriptions of the shape and the size of the environment. The two sexes also equally noted that they had studied the environment by wall-following, calibration and free walk. Moreover, no gender difference was observed in spatial behavior, and females and males followed the same phases of exploration. There was no significant gender difference in the overall area covered during exploration ($t$-test, $t_5$=0.89, n.s.) or in the cumulative number of visits to the various areas ($t$-test, $t_8$=0.81, n.s.). Both female and male subjects significantly increased travel velocity in the course of the 10 min observation, as described above.

Paths of progression were not affected by the landmarks (e.g. door, curtain, etc.). This is implicit in the finding that the most visited room area differed among the 10 subjects. That is, no two subjects showed the highest incidence of visits to the same location. Moreover, ranking the room areas according to the cumulative visits paid to each area revealed that the most visited areas with landmarks (a total of six areas) were ranked 3rd, 12th, 14th and downwards in the 48 room areas. Thus, the location of landmarks did not seem to affect the subjects' paths of progression.

## DISCUSSION

The construction of a cognitive map constitutes a process by which an individual acquires information about the environment and utilizes it in finding its way around. The present study aimed at identifying and analyzing the behaviors that underlie this process in human subjects. Blindfolded subjects were introduced into an unfamiliar empty room and asked to move incessantly for 10 min. Analysis of the subjects' paths of progression and patterns of exploration revealed the following sequential behaviors: (1) looping – returning to the origin of their path; (2) wall-following – circling the perimeter walls; (3) step-counting – commencing from a typical posture to walking at a steady pace toward the opposite wall; (4) cross-cutting – progressing toward the opposite wall through the center; and (5) free traveling – frequent cross-cutting and abandoning of the walls for longer periods of time. In the following discussion we describe these behaviors and their possible function in the context of a conceptual framework for the dynamics of cognitive mapping, termed the SIRN approach (Haken and Portugali, 1996).

### Behaviors involved in the construction of spatial representation

Humans and animals are able to construct a spatial representation of the external environment. Such a representation is termed a 'cognitive map' (Tolman, 1948). Cognitive mapping refers to the process of encoding spatial information, processing it, constructing a cognitive map, and storing it as an internal representation (Portugali, 2004). When a human or an animal encounters an unfamiliar environment, the mapping system first searches for a match between the external environment and a repertoire of stored internal representations from previous experience (Portugali, 2005). Cognitive mapping is thus assumed to be a process of continuous updating of any current representation as a consequence of changes in the perceived environment (O'Keefe and Nadel, 1978).

In order to construct a representation of an unfamiliar environment, the explorer initially relies on an egocentric frame of reference (Kallai et al., 2007; Sholl, 1996). That is, the explorer acquires information provided by the environment in relation to their own location (as opposed to a 'bird-like view'). When spatial information is scarce, for example in homogeneous environments or under poor visual conditions, the explorer may solely rely on self-generated cues. Such a process, known as 'path integration' or 'dead reckoning', enables the traveler to know the distance and direction of the current position with respect to the point of origin of travel (Etienne et al., 1998; Mittelstaedt and Mittelstaedt, 1980). An explorer that performs path integration can be regarded as acquiring an egocentric representation, as movement and self-location are determined in relation to elements in the environment (Benhamou et al., 1990). Looping is a specific mode of traveling in relation to path origin (Zadicario et al., 2005), and is consequently suggested to be based on path integration (Avni and Eilam, 2008; Zadicario et al., 2005). In other words, looping is an egocentric mechanism of exploration in which the explorer travels in a circular path that closes at the path origin. This mode of exploration has previously been observed in animals subjected to unfamiliar environments, especially under conditions of poor visibility (Avni et al., 2006; Bengtsson et al., 2004; Conradt et al., 2000; Conradt et al., 2003; Zadicario et al., 2005). For example, the diurnal fat sand rat (*Psammomys obesus*) explored a dark arena first by looping and then by wall-following (Avni and Eilam, 2008). In the present study, two subjects initiated exploration by looping back to their point of origin, then changed to progression along the walls. This transition probably reflects a preference to rely on the physical structure of the environment rather than on path integration, where position and orientation are calculated continuously and are thus prone to cumulative errors (Benhamou et al., 1990; Etienne et al., 1998). Nevertheless, immediate looping was performed by only two of the 10 tested subjects, whereas the others immediately clung to the physical environment (room walls). As detailed below, wall-following is another egocentric mode of traveling in which, unlike looping, routes are anchored to the physical environment.

In the present study, all subjects displayed wall-following, in which they circled the perimeter (Fig. 2). Wall-following has been described as moving along edges (Creed and Miller, 1990) or as the tendency to move while maintaining mechanical contact known as 'thigmotaxis' (Fraenkel and Gunn, 1961). This behavior is prominent when encountering an unfamiliar environment (Kallai et al., 2007) and contributes to the construction of environmental representation (MacEachren, 1992). Wall-following has been described in rodents (Hoffman et al., 1999), as well as in blind people, who utilize it as an initial tactic when exploring an indoor environment (Jacobson, 1993). In a naturally blind rodent, the mole rat (*Spalax ehrenbergi*), following the perimeter of the area was suggested as a phase of acquiring the shape and size of the environment (Avni et al., 2008). Wall-following behavior may be considered as an egocentric mechanism (self-to-object relationship), as movement and self-location are determined in relation to an external reference, in this specific case the room walls. Together, looping and wall-following are egocentric mechanisms in which the explorer sets their path in relation to an external reference. In looping, the external reference is the origin of the path and in wall-following it is the physical boundary. These initial egocentric mechanisms are used by the explorer to form spatial relationships between landmarks (object-to-object relationship), and to learn the structure and dimensions of the environment, as highlighted by step-counting. Thus, the egocentric phases of looping and wall-following, together with the phase of step-counting, are integrated to construct an allocentric spatial representation from the shape, size and landmark relationships in the environment.

Notably, by the end of the present test, all subjects had comprehended the geometry of the room, and some also accurately reported its dimensions. Cheng and Newcombe (Cheng and Newcombe, 2005) suggested that a primal stage in establishing a cognitive map is that of acquiring the geometric properties (e.g. principle axes) of the environment (Cheng and Gallistel, 2005; Gallistel, 1990) (but see McGregor et al., 2006; Pearce et al., 2004). In addition, it was suggested that spatial calibration is another primal stage in the acquisition of a global environment image (Avni et al., 2008). When forming a cognitive map, the subject has a stable image of the surrounding environment (allocentric representation). In the present study, this was well manifested in the emergence of the first cross-cutting, when subjects abandoned the walls and progressed to the opposite wall, adjusting their locomotion to avoid bumping into it. Accordingly, the first cross-cut demarcated the acquisition of allocentric representation, reflected in directed travel through the center toward another wall. This first cross-cut substantially differed from the seldom-displayed previous travel through the center, which seemed more like undirected wandering that ended in bumping into a wall (see supplementary material Movie 1). Having taken the first cross-cut, subjects then traveled freely throughout the room along a variety of paths, with numerous cross-cutting and wall-abandoning for longer periods of time (Fig. 4). Thus, the first cross-cut attests that the explorer has acquired a representation of the environment, according with the well-accepted notion that acquisition of a map is represented by the ability to perform shortcuts (O'Keefe and Nadel, 1978; Tolman, 1948). All in all, egocentric exploration (looping and/or wall-following), is used by the explorer to gather spatial information (e.g. metric, geometric and topological characteristics), which serve for the construction of allocentric representation (as explicit in cross-cutting and free traveling).

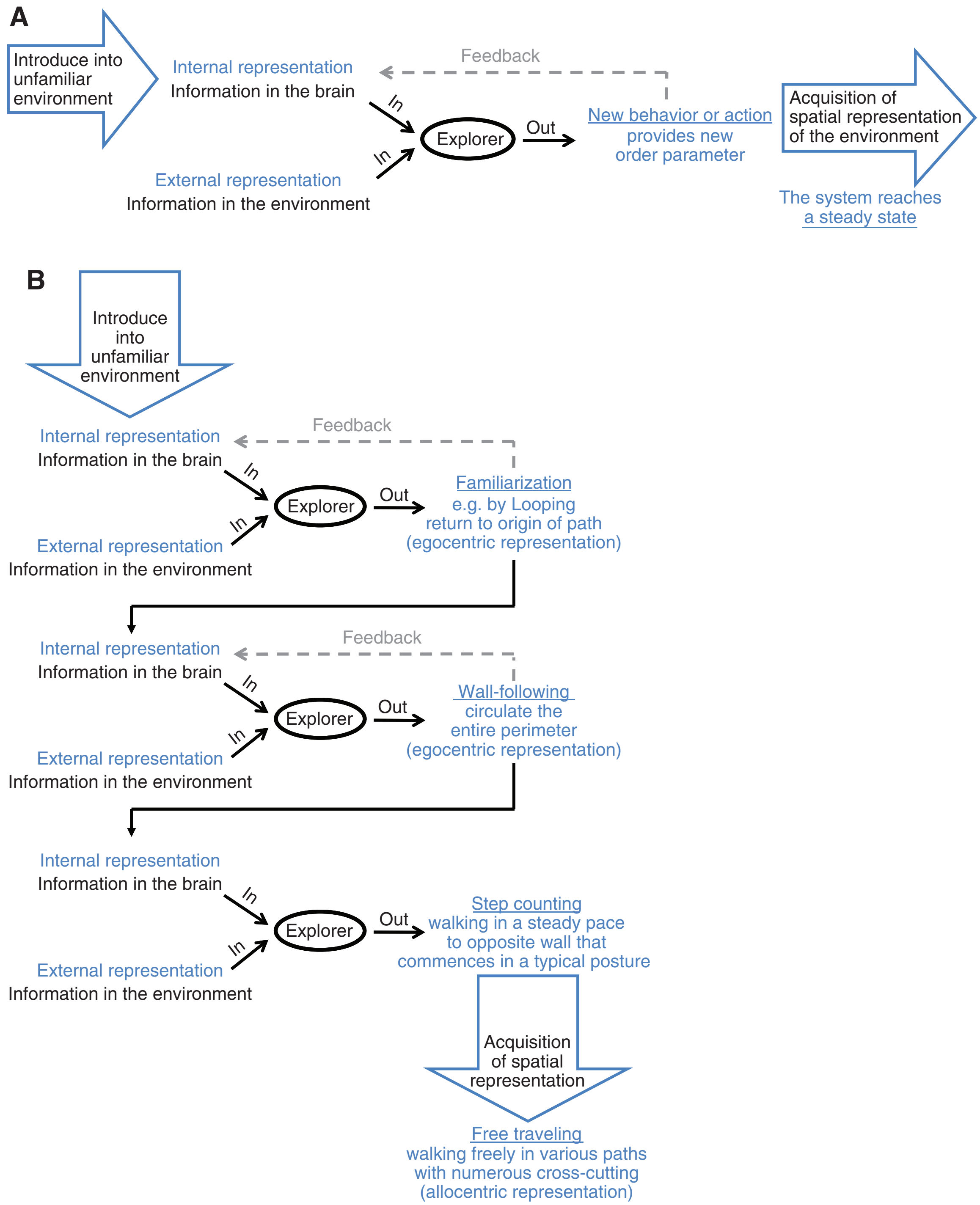


Fig. 5. (A) The synergetic inter-representation networks (SIRN) model offers a self-organized cognitive system subjected to the dynamic interaction of external and internal information. This dynamic interplay creates order parameters by means of a feedback process that ultimately brings the system to a steady state, producing the cognitive map. (B) The blindfolded human subjects constructed a cognitive map of the unfamiliar environment by means of a gradual and sequential interaction between internal and external representations. This process is reflected in different exploratory behaviors, with the last behavior representing the establishment of a cognitive map.

### Conceptual framework for the construction of spatial representation

So far, we have shown which behavioral patterns the blindfolded subjects utilized to construct spatial representation of an unfamiliar environment. These patterns unfolded in a typical order, and the first cross-cut through the center demarcated the acquisition of spatial representation. We now present the dynamic interplay between the physical environment and the behavior of the explorers in the course of cognitive mapping.

The construction of spatial representation is a gradual and dynamic process of gathering information from the physical environment and constructing and updating the internal image of that environment. During this process, the explorer performs new behaviors or actions to gather spatial information. Such an interplay between the internal and external representation of the environment is illustrated by a spider building its web (Portugali, 2002). At the start, the spider constructs a small net and is therefore confined to moving in a small area. Upon expanding the web, the spider is able to move in a larger environment. In fact, this is a sequential process in which the spider constructs the space for its subsequent traveling. The action of the spider thus determines the physical environment in which it can move (Portugali, 2002). This notion of cognitive mapping as a product of the dynamic interaction between internal and external representations was formalized by Haken and Portugali (Haken and Portugali, 1996) as the SIRN model. The basic proposition of the SIRN model is that brain and cognition are self-organizing systems that sequentially interact with the physical environment to produce an order parameter, which is then recruited into the interaction, resulting in another order parameter, until a steady state is reached (Fig. 5A). In the same vein, subjects in the present study constructed a cognitive representation in a dynamic and sequential process that was displayed by their explorative behaviors, as illustrated in Fig. 5B and in the following description.

The familiarization behaviors of looping and partial wall-following provided the cognitive system with an order parameter of partial external information. Because the system tends to reach a steady state, it elicited the wall-following behavior. In this subsequent phase, the physical boundaries of the environment determined the subjects' routes of progression, providing information about the layout of the room. However, as in the case of the spider building its web, subjects performed a further behavior of step-counting in order to determine the dimensions of the environment in which they could move. The acquisition of the geometric and metric properties of the environment acts as an order parameter that brings the system to a steady state – the formation of a cognitive map. The phenotype of the steady state was free travel, and its emergence was clearly marked by the first cross-cut. The acquisition of a cognitive map was also expressed in the ability of all subjects to sketch the shape, locate landmarks and provide the dimensions of the test environment. The present study thus validates the dynamics of cognitive mapping according to the SIRN model and provides a conceptual framework for the dynamic interplay of internal and external representations.

The present study demonstrates the importance of geometric and metric properties of the environment in establishing spatial representation. To substantiate the present results, further testing of blindfolded subjects in an unfamiliar environment with an irregular shape will enable the subject to encounter an external environment that substantially differs from the repertoire of stored internal representations. Similarly, testing blindfolded subjects in a large-scale unfamiliar environment will have an impact on acquisition of the geometry of the environment. These tests may highlight the effect of scale and boundaries on the construction of spatial representation. They may also extend the use of egocentric mechanisms involved in the construction of spatial representation and further validate the SIRN model as a framework for this dynamic process.

## APPENDIX

Each subject was requested to fill out a questionnaire after testing. The questionnaire was given after the blindfolded subject had been led by the experimenter outside the test room and the blindfold had been removed. The questionnaire comprised three open questions, as follows:

What was the shape of the environment? (Description in words and sketch.)

What was the size of the environment?

Was there a certain method that you utilized when traveling in the environment?

The questionnaire also included 10 questions in which the subjects were asked to rate the extent of their answers using a 5-rank scale, as follows:

Did you use the borders of the environment in your travel?

Did you use certain properties of the environment in your travel?

Did you feel that the starting point had any importance?

What was your confidence level at the start of the test?

What was your confidence level in the middle of the test?

What was your confidence at the end of the test?

What was your anxiety level at the beginning of the test?

What was your anxiety level in the middle of the test?

What was your anxiety level at the end of the test?

By the end of the test, had you acquired familiarity with the environment to a level that allowed cross-cuts or returns to specific locations?

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