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Remembering object position in the absence of vision: Egocentric, allocentric, and egocentric decentred frames of reference

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Abstract. In three experiments we examined whether memory for object locations in the peripersonal space in the absence of vision is affected by the correspondence between encoding and test either of the body position or of the reference point. In particular, the study focuses on the distinction between different spatial representations, by using a paradigm in which participants are asked to relocate objects explored haptically. Three frames of reference were systematically compared. In experiment 1, participants relocated the objects either from the same position of learning by taking as reference their own body (centred egocentric condition) or from a 90° decentred position (allocentric condition). Performance was measured in terms of linear distance errors and angular distance errors. Results revealed that the allocentric condition was more difficult than the centred egocentric condition. In experiment 2, participants performed either the centred egocentric condition or a decentred egocentric condition, in which the body position during the test was the same as at encoding (egocentric) but the frame of reference was based on a point decentred by 90°. The decentred egocentric condition was found to be more difficult than the centred egocentric condition. Finally, in experiment 3, participants performed in the decentred egocentric condition or the allocentric condition. Here, the allocentric condition was found to be more difficult than the decentred egocentric condition. Taken together, the results suggest that also in the peripersonal space and in the absence of vision different frames of reference can be distinguished. In particular, the decentred egocentric condition involves a frame of reference which seems to be neither allocentric nor totally egocentric.

1 Introduction

According to Carlson-Radvansky and Irwin (1994), we can use different frames of reference to represent the locations of objects in the environment. The frame of reference establishes a correspondence between the mental representation of space and the physical or perceived space. A reference frame is a coordinate system in which locations can be specified along different dimensions: two main reference frames are, for example, the egocentric and the allocentric ones. In the former, the spatial relations are represented with reference to the self and to the observer's body; in the latter, spatial relations are represented independently of the self, on the basis of coordinates external to the body, which, in some cases, can be particularly stable. According to Wexler (2003), the egocentric frame is subjective and centred on the eye and therefore fixed to the head, while an allocentric frame is objective and earth-fixed. Perceiving spatial information in an allocentric frame is perhaps the ultimate type of spatial constancy. The observer can see whether an object is moving at all, rather than moving relative to the observer. In the allocentric frame, the world can be assumed to be stable and the representations of objects and spatial relations do not have to be updated during movement. On the contrary, in the egocentric frame, information is provided by retinal data and only includes data on relative motion between object and observer.

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To convert this to an allocentric frame, the movement of the eyes through space, as the result of eye rotation and head movement must be evaluated and added to relative motion (Wexler 2003). Similarly, other studies (see Bryant 1997) have distinguished between the egocentric frame of reference (or viewer-centred) and the allocentric frame (or environmental). The egocentric frame is defined by the three body axes (head – feet, front – back, left – right), or sometimes in a retinocentric or head-centric coordinate system. On the other hand, the allocentric frame is composed of orthogonal axes set outside the observer. In principle, these axes could be oriented any way, but typically one axis corresponds to the gravitational axis of the world, and the others to the two horizontal directions along the plane of the local terrain. The axes may be centred on some prominent landmark in the environment or aligned with global features (eg cardinal compass directions). Such a distinction can also be applied to spatial-orientation strategies (Wang and Spelke 2000; Jordan et al 2004).

The distinction between egocentric and allocentric representations overlaps to a certain extent with the distinction between viewpoint-dependent and viewpoint-independent representations (Nadel and Hardt 2004). In particular, in the viewpoint-dependent representation, knowledge is represented in a format that reflects the specific experience relative to how things appear from a particular vantage point. In the viewpoint-independent representation, that vantage point is absent; therefore in some sense it must be the case that allocentric representations are necessarily integrated across multiple experiences.

Recently, the distinction between egocentric and allocentric representations has been supported by neuropsychological data. In particular, the hippocampal complex was found to be critical for allocentric spatial learning and recall, whereas other brain systems, such as the caudate nucleus, played a critical role in egocentric space. According to Nadel and Hardt (2004) allocentric and egocentric spatial information is handled separately, and the hippocampal information is particularly involved with allocentric but not with egocentric representations whilst the latter appears to be the province of the caudate nucleus. Parslow and colleagues (2004), and Shelton and Gabrieli (2004), however, emerged with rather less definite results as regards this distinction, whereas Bohbot et al (2004) allocate clearly distinct functions to the hippocampus and the parahippocampal formation.

A number of pioneering studies on the effects of selective patterns of brain damage in humans (Semmes et al 1963; Butters et al 1972) and monkeys (Pohl 1973) have revealed dissociations between the performance of spatial tasks that use the body as a reference point and those that require a reference point relative to a spatial arrangement of objects in the external environment. However, it is difficult to draw strong conclusions from these studies because they involve complex tasks which differ greatly according to whether they require a body-centred or an environment-centred orientation. So far, few behavioural studies with adults have successfully differentiated between egocentric and allocentric coding (Bridgeman et al 1979; Tipper et al 1992). Furthermore, it was only with the study of Woodin and Allport (1998) that clear evidence of a behavioural dissociation between egocentric and allocentric representations in human adults emerged. These authors demonstrated that the two representations are genuinely functionally independent, distinguishing between body-centred and environment-centred representations at the behavioural level.

Even though the distinction between an egocentric and allocentric perspective is largely accepted, additional representations may also exist. For example, an allocentric representation is not necessarily independent from a personal perspective and it can be also in some ways dependent on the individual's position, especially when it refers to relatively small environments. Grush (2000) observed that the allocentric term can be used with different meanings and claimed that there are at least four different types of situations associated with 'allocentric' representations: (a) egocentric space with a non-ego object reference point; (b) object-centred reference frames; (c) virtual points of view (ie maps); (d) 'nemocentric' maps. From the perspective adopted in the present study, the first two instances appear of particular interest. To differentiate between them, the following example was given by Grush (2000): "I am in a room that is empty except for an upright statue of an elf, a lamp that is situated above the statue, and Jones, who is lying down at one side of the room". In the (a) egocentric space with a non-ego object reference point, I might say that the statue is to the left of Jones, while still using an egocentric space. That is, I assume a space with myself at the origin and myself as setting up the axes of left – right, above – below, front – back, etc. I then use one object in this space as a reference point for locating another object in this space: locate Jones, and then move to the left (where left means left as constituted in my egocentric space), and there you will find the statue. This is a tricky case, because it can look like an object-centred reference frame, but really it is not. Notice that the statue may not be to Jones's left at all; it may be in front of, or behind or even to the right of Jones, as judged from Jones's egocentric space. In some sense, this representation is decentred because it is based on an object, but is egocentric because it involves the subject's space. A more complete allocentric representation is involved with (b) object-centred reference frames where an object serves as the origin of an object-centred space. Consider Jones's thought that the lamp is above the statue. Since Jones is lying down, the lamp is really to the left of the statue in his own egocentric space. Jones is using a space that is centred on, and whose axes are provided by, the object itself. In this case, above means above from the point of view of the statue of the elf, not just above the statue as a reference point. Such a reference frame might be centred on any object or a person other than oneself. Similarly, Levelt (1984) and Bryant (1997) refer to the 'object-centred reference frame' as that frame in which the axes are defined by the intrinsic sides of a referent object.

A problem related to the distinction between different representations is that they do not take into consideration the fact that different cognitive implications are associated with the space within the subject's reach (ie the peripersonal space—Rizzolatti et al 1997) and the extrapersonal space. In particular the allocentric representations are mainly based on the extrapersonal space whereas the egocentric representations seem to involve more frequently both types of space. According to Woodin and Allport (1998), a possible explanation of this is that large layouts are perceived as real spatial environments in which it is possible to move about, leading to environment-centred coding, whereas small-scale layouts are perceived more as an object, leading to relatively view-dependent or egocentric coding.

It is not clear to what extent the allocentric – egocentric distinction applies when the distinction between extrapersonal and peripersonal space is controlled for and, in particular, the peripersonal space is considered. The representation described by Grush (2000) for egocentric space with a non-ego object reference point appears critical as the egocentric space should assume a particular strength owing to the fact that the non-ego object is still within the subject's reach.

A further problem in all these distinctions is that they are based on representations derived from visual experience and it is not clear if they are applicable to cases in which the body is not supported by vision. For example, Conti and Beaubaton (1980) found that the accuracy of pointing to a luminous target is lower in complete darkness than when a structured visual field is present. According to Woodin and Allport (1998), this would suggest that the structured visual field gives rise to an allocentric reference frame. In this situation the pointing would be more accurate than when only a body-centred coding of the position of the target is available. However, little is known about a spatial representation generated in a dark environment or about spatial representations of blind individuals.

Imagine, for example, yourself seated in front of a table at night in complete darkness and having to learn the locations of certain objects. In this instance is the distinction between an egocentric and an allocentric representation still valid? What features critically define the allocentric representations?

To test for these effects in the present study, a non-visual test, named 'blind exploration test' (BET), was employed. Participants were presented with a series of objects located in different positions on a table and were asked to haptically explore them in the absence of vision.

According to Klatzky and Lederman (2003), while touching a sparse set of locations without vision people form one or more types of representation on the basis of which they attempt to derive answers to spatial questions about the contacted points. On the one hand, when spatial representations are mediated by vision, the distinction between egocentric and allocentric is masked, owing to the process of integration by the visual system. On the other hand, when the spatial representation systems work in the absence of vision, the distinction between different types of representation is more marked. Indeed, the spatial representation can be produced also by other systems, such as, for example, the haptic and the kinetic ones. Moreover, considerable errors normally occur when people derive angle or distance estimates from haptically explored configurations (Klatzky and Lederman 2003), and this could also contribute to emphasise the difference between the different types of representation.

Here we examine a situation in which the spatial positions of some objects are learnt without the integration of the visual system, in a condition of total darkness.

Three experiments were carried out to test whether the egocentric representations can favour the learning and the recalling of the spatial position of the objects in total darkness with respect to the allocentric representations, and whether it is possible to distinguish between the reference frames (a) egocentric space with a non-ego object reference point and (b) object-centred reference frames, as suggested by Grush (2000).

2 Experiment 1

The first experiment was designed to differentiate between centred egocentric and allocentric representations. As shown by a number of studies in the literature such differences are well documented (Klatzky 1998; Feigenbaum and Morris 2004; Mou et al 2004; Holmes and Sholl 2005); thus, we start from the assumption that differences between the egocentric and allocentric representations do exist. Therefore, if our task is a sensitive measure of the two representations, differences are expected to emerge.

2.1 *Method*

2.1.1 *Participants.* Sixteen university students (eight male and eight female), aged between 20 and 27 years, participated in the experiment. All the participants were right-handed with normal vision.

2.1.2 *Stimulus materials.* The participants were presented with a 50 cm $\times$ 50 cm cardboard square with fixed reference points. In the middle of the lower perimeter (25 cm from the left and from the right corners) a small coin (0.1 euro) was glued. The coin represented the starting point for the exploration and for the centred egocentric test condition. This point was labelled Home. At the centre-left side of the cardboard (25 cm from the higher and the lower corners) another small coin (0.1 euro) was glued. This point was labelled School and was the starting point for the allocentric condition.

In every trial the participants touched three objects of similar shape and dimension with their right hand, guided along the corresponding pathway by the experimenter. The first object to be explored was point A, which consisted of a penknife (dimensions 2.5 cm $\times$ 1.5 cm). The second object was point B and consisted of a coin (diameter 2.5 cm).

The third object was point C, which was another similar coin (diameter 2.5 cm) but with paper glued around it.

Criteria for building the configurations. 16 different configurations were arranged on the 50 cm × 50 cm cardboard. In order to harmonise the distribution of the three objects to be explored, some criteria were followed when building the 16 configurations. First, the sum of the distances Home – point B (H – B) and Home – point C (H – C) was equal to the sum of the distances School – point B (S – B) and School – point C (S – C). The sum was constant through all the 16 trials and was 50 cm. The H – B distance always assumed different values for each configuration, that is 8, 10, 12, 14, 16, 18, 20, 22, and 28, 30, 32, 34, 36, 38, 40, 42 cm. Point B was located in the lower part of the square half the time (for values lower than 25 cm) and in the upper part of the square, in the remaining trials (for values higher than 25 cm). The same procedure was used for the S – B distance. The values assumed were the same as for the H – B distance. Point B was positioned in the left part of the square, half the time (for values lower than 25 cm) and in the right part in the remaining trials (for values higher than 25 cm). The cardboard was divided into four quadrants (Q1 up-left, Q2 up-right, Q3 down-right, Q4 down-left). The position of point B was balanced so that it occurred in all the four quadrants of the cardboard. Hence point B occurred 4 times in each quadrant. The position of point C was determined with the formulas S – C = 50 cm – S – B and H – C = 50 cm – H – B. An example is presented in figure 1. Point A always occurred in the lower-left quadrant and was located in the middle of the diagonal between the lower-left corner and point B or C closer to the corner. Appendix 1 shows the coordinates for the B and H points starting from the H and S points.

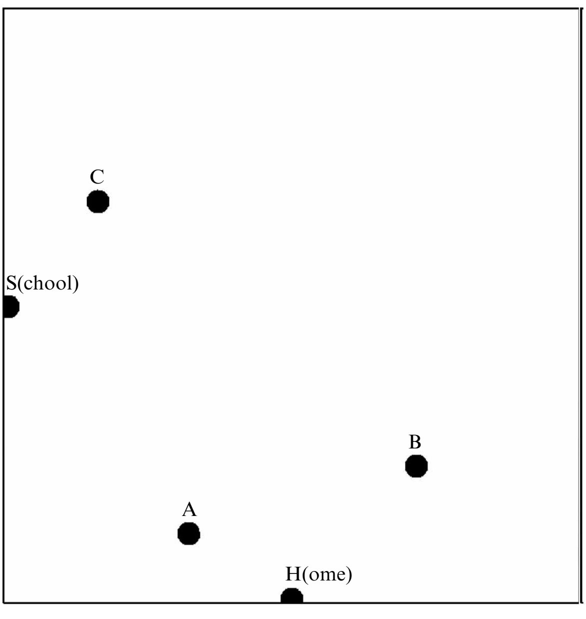

Figure 1. Example of the blind exploration test (BET) material employed in the present study.

2.1.3 *Procedure.* Participants were informed that they were participating in an experiment on spatial memory. They were instructed outside the experimental room. After the instructions, they were blindfolded and were accompanied by the experimenter to the experimental room. As a result, they did not see the experimental room. This procedure was adopted to avoid participants knowing the room geometry. In fact, room geometry per se has been shown to be a strong cue for object-locating tasks. Wang and Spelke (2000) found that room geometry is characterised by an enduring, observer-free, map-like representation, which can eliminate the effects of disorientation.

After entering the room, participants were invited to take a seat at the Home point and to explore the three objects. The three objects had to be explored only with the right hand. Participants were required to remember the original positions of the three objects placed on the square cardboard and were requested to keep the left hand under the table and not to use it.

Participants were blindfolded so as not to have access to external visual cues. Indeed, if participants could not use external visual cues in the cardboard arrangement, then we expected their reference points to be those given haptically by the experimenter.

In the exploration phase, the participant was seated at the Home position and the experimenter guided his/her right hand along the perimeter of the cardboard making a complete clockwise exploration. Such a perimeter exploration was also necessary to let participants know the locations of Home and School points. Then, starting from the Home point, the experimenter guided the participant's right hand toward each object, moving it linearly from one location to the next, according to the following sequence: H – A – B – C – A – H. We preferred a guided exploration instead of a free exploration to be sure that the three objects were always explored in the same sequence and to control for the use of reference points (Home and School).

The exploration phase lasted about 8 s and was followed by a retention interval of 10 s. During this interval, the participant was asked to stand up, turn 90° and sit on the chair facing the H point (centred egocentric condition) or to stand up and sit on the chair facing the S point (allocentric condition). During this phase, the experimenter removed the three objects (A, B, C) from the square cardboard on the table. Once the participant was seated, the test phase started. The participant was guided again along the perimeter of the cardboard. Then, starting either from the H point (centred egocentric condition) or from the S point (allocentric condition) the participant was asked to indicate with his/her finger the original positions of the objects in B and in C. In order to avoid a route-like representation (Tversky 1991), in which the three objects are sequentially imagined as an itinerary, the position of point A was never tested. In fact, point A was directly connected to Home (no spatial inference), while points B and C were the result of spatial inference processes. For half the trials, point B was required to be recalled first; for the remaining trials point C was required to be recalled first. The experimenter marked the response of the participant on the cardboard. After the first point was indicated, the participant was requested to go back to the starting point and then to indicate the second point.

Overall, each participant performed 8 centred egocentric and 8 allocentric trials. All the 16 trials were randomly presented. Half of the centred egocentric and half of the allocentric trials followed the order of recall 'B first – C second', while the remaining trials followed the reverse order. Before starting the experiment, two practice trials were carried out and the participant was informed about the different conditions and the different orders of recall.

Data scoring. Two measures of performance were taken into account: the linear distance error is a measure of the distance in centimetres between the original position of an object and the position indicated by the participant, the angular error is the angular difference between the original direction of the point and the direction pointed to by the participant. In the centred egocentric condition the angle corners were computed with the vertex in H. In the allocentric condition, since the participant during the test had the School landmark S as a reference point, the angle corners were computed with the vertex in S. Consequently, for each participant there were 32 linear distance errors (2 points by 16 configurations) and 32 angular errors (2 points by 16 configurations).

2.2 *Results*

Table 1 shows the descriptive statistics for the centred egocentric and allocentric conditions. Two within-subjects 2×2 ANOVAs were computed, one for each measure of performance, with type of condition (allocentric versus centred egocentric) and type of point (point B versus point C) as factors.

Table 1. Descriptive analyses for the egocentric and the allocentric conditions of experiment 1.

Error	Egocentric		Allocentric	
	mean	SD	mean	SD
Distance on point B/cm	5.32	2.13	7.14	1.92
Distance on point C/cm	5.67	2.53	7.05	2.35
Angular on point B/°	8.74	4.11	12.22	5.05
Angular on point C/°	10.41	5.62	12.74	5.36

For all the analyses α was set at $p < 0.05$. Levels of p between 0.05 and 0.08, if accompanied by a 'large effect' of η^2 (> 0.15), were reported as marginally significant.

2.2.1 *Linear distance errors.* Results showed a significant difference between the allocentric and the centred egocentric performance ($F_{1,15} = 5.95$, $p < 0.05$, $\eta^2 = 0.30$). As expected, the mean error was greater in the allocentric condition. No difference emerged for type of point ($F_{1,15} < 1$).

2.2.2 *Angular errors.* A similar ANOVA revealed a marginal main effect of condition ($F_{1,15} = 4.20$, $p = 0.058$, $\eta^2 = 0.23$), indicating that the errors in the allocentric condition tended to be larger than in the centred egocentric condition. Also the main effect of type of point was marginally significant ($F_{1,15} = 3.58$, $p = 0.078$, $\eta^2 = 0.20$), suggesting that point C tended to produce more errors than point B.

Further analyses showed that the effects due to the order of recall of the points ('B first – C second' versus 'C first – B second') and gender (male versus female) were not significant.

2.3 *Discussion*

Results of experiment 1 showed that the egocentric and the allocentric frames of reference can be distinguished also in a peripersonal space explored in absence of vision and our BET task is a sensitive task in highlighting differences between types of representation. Such differences were more marked when the linear distance errors were considered as the dependent variable. When considering the angular errors as the dependent variable, the same pattern of results emerged, even though the effect was weaker. Moreover, experiment 1 showed that results depended neither on the order of recall nor on the gender of participants and for this reason these variables were not taken into account in the following experiments. In experiment 2 we analysed whether an egocentric position in reference to the body, but with a starting point different from the body location (decentred egocentric), produced a different kind of representation. This is a particular situation named by Grush (2000) as 'decentred egocentric' which can still be considered egocentric, but where one object external to the body is taken as a reference point for locating another object.

3 Experiment 2

The main objective of this experiment was to explore the differences between two egocentric conditions: a 'centred egocentric' and a 'decentred egocentric' representation. We wanted to test whether a decentred egocentric representation, which requires a starting point different from the body, even though egocentric, is different from the 'centred egocentric' condition, in which the starting point matches the body. If we were to find differences, then the supposition that a 'centred egocentric' and a 'decentred egocentric' situation represent two distinct and separable spatial representation systems would be supported. If not, then the two situations would be relying on the same, single egocentric representation.

3.1 *Method*

3.1.1 *Participants.* Twenty university students (ten male and ten female), aged between 21 and 30 years, participated in the experiment. All the participants were sighted and right-handed.

3.1.2 *Materials.* The same materials as in experiment 1 were used. Point S was again labelled School and was the starting point for the 'decentred egocentric' condition.

3.1.3 *Procedure.* The same procedure as in experiment 1 was followed, both as regards the initial exploration and the retention interval. The only difference was that the allocentric condition was substituted with the decentred egocentric one, in which participants, tested individually, remained in the same position as in the egocentric condition, but began testing with their right hand in the S location.

For the data scoring, the same criteria as in experiment 1 were employed. In the egocentric condition the angle corners were computed with the vertex in H. In the 'decentred egocentric' condition the angle corners were computed with the vertex in S.

3.2 *Results*

Table 2 shows the descriptive analyses for the egocentric and decentred egocentric conditions.

Table 2. Descriptive analyses for the centred egocentric and decentred egocentric conditions of experiment 2.

Error	Centred egocentric		Decentred egocentric	
	mean	SD	mean	SD
Distance on point B/cm	5.52	2.85	7.56	2.00
Distance on point C/cm	5.83	2.64	8.47	2.33
Angular on point B/°	13.91	7.96	15.59	5.81
Angular on point C/°	14.71	7.30	15.43	5.14

Two repeated-measures 2×2 ANOVAs were computed, one for each measure of performance, with type of condition (centred egocentric versus decentred egocentric) and type of point (point B versus point C) as factors.

3.2.1 *Linear distance errors.* Results showed a significant difference between the decentred egocentric and the egocentric performance ($F_{1,19} = 13.20$, $p < 0.05$, $\eta^2 = 0.42$). As expected, the magnitude of errors was higher in the decentred egocentric condition. Also the main effect of type of point was significant ($F_{1,19} = 7.03$, $p < 0.05$, $\eta^2 = 0.28$) with C errors higher than B errors.

3.2.2 *Angular errors.* The same pattern of results seems to emerge, since the decentred egocentric condition produced more errors than the centred egocentric condition, though the differences were not significant.

3.3 *Discussion*

Results of experiment 2 showed that there were differences between the decentred egocentric and the egocentric performance. This occurred only when the 'linear distance errors' were considered. The fact that the error was greater for point C than for point B suggests that people tended to use a sequential memory of the original exploration path, and consequently that the double inference required for establishing the location of C created greater difficulties. As mentioned in the discussion of experiment 1, the measure of the angle error is not a very sensitive measure and, therefore, when considering the angle error, differences were less clear than when considering the linear distance errors.

When observing the pattern of results of experiment 2, one might argue that the motor response between the egocentric condition and the decentred egocentric condition was not comparable, since in the latter case participants had to make a more complex movement of their hand, from their body to point S and then from point S to the required object. Thus, it is possible that this fact contributed to the result that participants were more accurate in pointing to the front than pointing to the right. This aspect was controlled for in experiment 3, designed to compare the egocentric decentred condition with the allocentric condition by a procedure requiring participants to point to the front in the allocentric condition and to point to the right in the decentred egocentric condition.

To sum up, results from experiment 2 showed that the decentred egocentric representation can be considered to be different from the centred egocentric representation. Indeed, the two performances were dissimilar. However, before considering the decentred egocentric condition as an independent representation, there is still the possibility that such a decentred egocentric representation is an allocentric representation. Indeed, in both cases an object external to the body is taken as a reference point for locating another object and this task may thus be considered an allocentric representation.

4 Experiment 3

The results of experiments 1 and 2 could suggest that an allocentric representation is just like a decentred egocentric representation, in that the same format of representation is maintained starting from a point external to the body. Therefore, in a third experiment we compared the decentred egocentric and the allocentric representations. Indeed, if we find differences when comparing the decentred egocentric and the allocentric performances, then we can hypothesise that they are not represented in the same manner, but may be associated with two different types of mental representations. In this case the term 'allocentric' would imply something more than a simple decentred egocentric representation. On the contrary, if the two performances are found not to be different, then one could conclude that the critical aspect of the 'allocentric' condition is the decentring of the starting point.

4.1 *Method*

4.1.1 *Participants.* Twenty university students (eight male and twelve female), aged between 21 and 23 years, participated in the experiment. All the participants were sighted and right-handed.

4.1.2 *Materials.* The same materials as in experiments 1 and 2 were employed. Point S was again labelled School and served as the starting point for both the decentred egocentric and the allocentric conditions.

4.1.3 *Procedure.* The same procedure and scoring as in experiment 2 was applied. However, in experiment 3, participants were tested with the decentred egocentric (starting to recall the objects' locations from the S location, as in experiment 2) and the allocentric condition (turning their body 90° to the S location), as in experiment 1.

4.2 *Results*

Table 3 shows the descriptive statistics for the decentred egocentric and the allocentric conditions.

Table 3. Descriptive analyses for the decentred egocentric and the allocentric conditions of experiment 3.

Error	Decentred egocentric		Allocentric	
	mean	SD	mean	SD
Distance on point B/cm	6.99	2.63	8.72	2.54
Distance on point C/cm	6.77	2.80	9.90	3.19
Angular on point B/°	19.23	8.59	21.11	7.38
Angular on point C/°	17.14	7.54	21.49	7.52

Two repeated-measures 2×2 ANOVAs were computed, one for each measure of performance, with type of condition (decentred egocentric versus allocentric) and type of point (point B versus point C) as factors.

4.2.1 *Linear distance errors.* Results revealed a main effect of condition ($F_{1,19} = 16.22$, $p < 0.05$, $\eta^2 = 0.47$), demonstrating that the magnitude of errors was higher in the allocentric condition. No difference emerged for type of point ($F_{1,19} < 1$). However, the interaction between type of condition and type of point was significant ($F_{1,19} = 5.27$, $p < 0.05$, $\eta^2 = 0.23$). A posteriori Tukey analyses showed that C errors tended to be higher than B errors only in the allocentric condition (marginal effect: $p = 0.058$), but not in the decentred egocentric one.

As shown in figure 2, the difference between the B and C points—unlike in experiment 2—did not occur in the decentred egocentric condition. In the allocentric condition there was a peak of errors for point C.

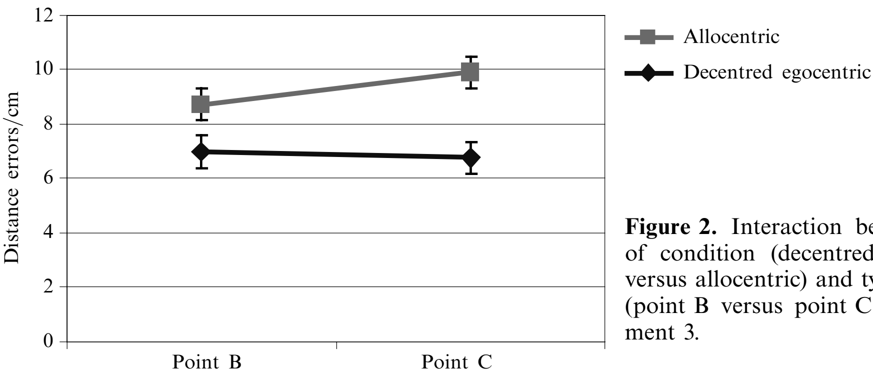

Figure 2. Interaction between type of condition (decentred egocentric versus allocentric) and type of point (point B versus point C) in experiment 3.

4.2.2 *Angular errors.* Results showed no significant difference. However, errors in the allocentric condition tended to be higher than in the decentred egocentric condition ($F_{1,19} = 3.43$, $p = 0.08$, $\eta^2 = 0.16$).

4.3 *Discussion*

The results of experiment 3 indicate that a decentred egocentric representation does not require the same processes as an allocentric one. Indeed, there were differences between the decentred egocentric and the allocentric performance. These differences were more evident when the 'linear distance errors' were considered and were very marginal when considering the angle error. Again, the measure of angular errors was less sensitive.

Given the results of experiment 3, we can confirm that a decentred egocentric representation is not an allocentric representation. In conclusion, experiments 2 and 3 were crucial for demonstrating that the decentred egocentric condition is neither similar to an egocentric condition, nor to an allocentric condition.

That a greater difficulty for point C was not present in the decentred egocentric condition may have been due to the fact that point C is slightly harder to locate (see marginal effects in previous experiments), and the differences appear when the task difficulty is stressed by the experimental condition (in this case, the allocentric condition).

5 General discussion

Different types of spatial representations within the peripersonal space were here explored in the absence of vision by means of a new test (the BET test).

According to Waller and Hodgson (2006) and Waller and Greenauer (2007), when people interact with an environment, two systems of spatial representation work simultaneously: (a) a transient egocentric representation system (online, dynamic, with transient codes) which works in real-time to enable immediate interaction with the environment, and (b) an enduring representational system (long-term-memory-based and stable over time), which works remotely and offline to enable people to judge the spatial relations of environments that are not immediately available to the senses. Similarly, Wang and Spelke (2000) found that, when humans are tested in small-scale environments, their ability to accurately locate objects appears to depend on representations of the current egocentric distance and direction of objects, with a process that continuously updates those representations over locomotion, and with an enduring representation of environment geometry which may serve as a basis for reorienting (Cheng and Gallistel 1984; Hermer and Spelke 1996). In the BET test the representations of distance and direction of objects were measured by means of the two variables of distance errors and angular errors. The enduring representation was controlled for by means of two fixed points (Home and School) and by the guided exploration of the perimeter of the cardboard. Such procedural details plausibly contribute to the reliability of the results which emerged from the BET test.

The results of the three experiments, taken together, show the possibility of a distinction between the centred egocentric, the decentred egocentric, and the allocentric frames of reference. In particular, results concerning the distinction between the centred egocentric and the allocentric frames mimic those of Klatzky and Lederman (2003). In their study (experiment 3) participants either replaced their fingers at the original location, or translated the finger configuration to a new location. Performance was better when participants replaced their fingers at the original location.

In fact, the distinction between centred egocentric and allocentric frames is well documented in the psychological literature (Klatzky 1998; Woodin and Allport 1998; Holdstock et al 2000; Wang and Spelke 2000; Burgess et al 2004; Feigenbaum and Morris 2004; Mou et al 2004; Wang 2004). However, when testing long-term memory for spatial layouts, egocentric and allocentric representations emerge as depending on the size of the layouts (Woodin and Allport 1998). For large spatial layouts lying beyond the reaching space (extrapersonal space), the accuracy of spatial memory is independent of the testing standpoint. However, for small layouts (peripersonal space), accuracy tends to decrease if the testing standpoint differs from the original viewing orientation (Presson et al 1989).

Nevertheless, the distinction between egocentric and allocentric was generally studied with vision and in the context of large extrapersonal environments. The two conditions (vision, large spaces) can facilitate the acquisition of two independent, allocentric versus egocentric representations. The present study shows that a similar distinction also applies to the peripersonal space explored haptically.

A further finding of this study is the existence of a third representation ie the decentred egocentric representation. In fact, the request of using, from an egocentric point of view, a reference point decentred with respect to the egocentric Home, ie the School, produced results which were different both from the egocentric standard condition and the allocentric one. Further evidence should support the present differentiation and control for possible external influences. For example, it is possible that the difference in the motor response for the egocentric and the egocentric decentred conditions (deliberately introduced in experiment 2, in order to have the prototypical situations of moving from the trunk or from a location within reach of the hand) had some negative influence on the performance, but this difference was presumably marginal, since in experiment 3 the simpler motor response produced a poorer performance.

According to Klatzky (1999), during manual exploration the subject's body provides a reference for the location of touched points in space. The cognitive neuroscience literature provides evidence for a multiplicity of different egocentric spatial coding systems in the primate brain (Bracewell et al 1991; Andersen 1995) with reference to many different parts of the body, including retina-, head-, trunk-, shoulder-, and hand-centred coding systems. For example, visual cells with spatial responses fully independent from the eye position are found to be involved in reaching responses (Gentilucci et al 1983; Fogassi et al 1992). Moreover, cell populations have been reported with both visual and tactile responses, whose spatial selectivity depends on, and moves with, the position of the animal's hand (Graziano and Gross 1995). In the light of these neuropsychological data on animals, it could be hypothesised that the centred egocentric representation would rely on a trunk-centred coding system, while the decentred egocentric representation might be thought of as relying on a hand-centred coding system. Indeed, in the decentred egocentric conditions, participants were required to dissociate the trunk position from the right-hand position, since they had to mentally rearrange all the objects' locations starting from the position of their right hand (that is the School point), since their trunk was in the Home point position.

Even if a possible correspondence between trunk-centred coding system and centred egocentric representation and between hand-centred coding system and decentred egocentric representation is still far from being definitively demonstrated in the present study, such a possibility might be taken into consideration for future behavioural research on humans. This does not exclude that these body reference points interact during encoding and/or are only partially used and that the less immediate not egocentric representations are only partially created during encoding and then completed, or even inferred, if necessary, when tested.

The decentred egocentric representation matches the notion of egocentric space with a non-ego object reference point proposed by Grush (2000), which, to date, had no known empirical evidence. Indeed, consistent with Grush's theory, the present findings show that the decentred egocentric representation is neither egocentric nor allocentric but it is midway between the two representations.

The decentred egocentric representation can be considered egocentric because the position of the body is the same both during the exploration and the test, but it is also in some respects similar to the allocentric, since the reference point is not centred on the body.

The decentred egocentric representation could also be seen as a kind of 'missing link', which directly connects the centred egocentric to the allocentric frames of reference. Consistent with this suggestion is an interpretation of the different frames of reference as being part of a continuum with different levels of abstraction. Such a continuum would start from the lowest level of abstraction, that is, the centred egocentric representation, through the decentred egocentric and end at the highest level of abstraction, that is, the allocentric level.

However, further research is needed to fully investigate the properties of the decentred egocentric frame of reference and whether it really represents a self-dependent system or not. Indeed, in the literature the allocentric and egocentric frames of reference are considered as underlying different representational systems. Despite the large research literature devoted to studying the allocentric and egocentric systems, and in particular their different forms of coding and how these systems develop and interact with one another (Holmes and Sholl 2005), very little is known about the forms of coding of the decentred egocentric system, how it develops, and how it interacts with both the egocentric and allocentric spatial systems.

Furthermore, it is worth noting that the distinction between egocentric and allocentric reference frames has found a number of applications in human navigation. On the contrary, nothing is known about the applications of the decentred egocentric system. Plausibly, the decentred egocentric frame of reference also has a role in spatial navigation. Indeed, spatial-cognition research identified the egocentric and allocentric reference frames as functionally relevant to direct spatial behaviour. For example, when considering spatial-navigation strategies, it is well known that subjects utilising the egocentric frame use meaningful landmarks (local focus) to navigate, orienting themselves as if they were within a 3-D environment and learning the location of specific targets and how often they have to turn right or left (Jordan et al 2004). In contrast, subjects utilising an allocentric strategy make use of mental spatial maps and orient themselves according to general landmarks (global focus) such as direction (north or south) or the position of the Sun (Jordan et al 2004). Possibly some spatial orientation strategies might also be based on the decentred egocentric point of view.

On the basis of this knowledge, it seems reasonable to hypothesise that the decentred egocentric frame could play an important role in spatial behaviour. One of the challenges of future research is to understand how this happens.

References

Andersen R A, 1995 "Coordinate transformations and motor planning in the posterior parietal cortex", in *The Cognitive Neurosciences* Ed. M S Gazzaniga (Cambridge, MA: MIT Press) pp 519 – 532

Bohbot V D, Iaria G, Petrides M, 2004 "Hippocampal function and spatial memory: Evidence from functional neuroimaging in healthy participants and performance of patients with medial temporal lobe resections" *Neuropsychology* **18** 418 – 425

Bracewell R M, Barash S, Mazzoni P, Andersen R A, 1991 "Neurons in the macaque lateral intra-parietal cortex (LIP) appear to encode the next intended saccade" *Society for Neuroscience Abstracts* **17** 1282

Bridgeman B, Lewis S, Heit G, Nagel M, 1979 "Relation between cognitive and motor-oriented systems of visual position perception" *Journal of Experimental Psychology: Human Perception and Performance* **5** 692 – 700

Bryant D J, 1997 "Representing space in language and perception" *Mind and Language* **12** 239 – 264

Burgess N, Spiers H J, Paleologou E, 2004 "Orientational manoeuvres in the dark: Dissociating allocentric and egocentric influences on spatial memory" *Cognition* **94** 149 – 166

Butters N, Soeldner C, Fedio P, 1972 "Comparison of parietal and frontal lobe spatial deficits in man: Extrapersonal versus personal (egocentric) space" *Perceptual & Motor Skills* **34** 27 – 34

Carlson-Radvansky L A, Irwin D, 1994 "Reference frame activation during spatial term assignment" *Journal of Memory and Language* **33** 646 – 671

Cheng K, Gallistel C R, 1984 "Testing the geometric power of an animal's spatial representation", in *Animal Cognition* Eds H L Roitblat, T G Bever, H S Terrace (Hillsdale, NJ: Laurence Erlbaum Associates) pp 409 – 423

Conti P, Beaubaton D, 1980 "Role of structured visual field and visual reafference in accuracy of pointing movements" *Perceptual & Motor Skills* **50** 239 – 241

Feigenbaum J D, Morris R G, 2004 "Allocentric versus geocentric spatial memory after unilateral temporal lobectomy in humans" *Neuropsychology* **18** 462 – 472

Fogassi L, Gallese V, Di Pellegrino G, Fadiga L, Gentilucci M, Luppino G, Matelli M, Pedotti A, Rizzolatti G, 1992 "Space coding by pre-motor cortex" *Experimental Brain Research* **89** 686 – 690

Gentilucci M, Scandolara C, Pigarev I N, Rizzolatti G, 1983 "Visual responses in the post arcuate cortex (area 6) of the monkey that are independent of eye position" *Experimental Brain Research* **50** 464 – 468

Graziano M S, Gross C G, 1995 "The representation of extrapersonal space: A possible role for bimodal, visual-tactile neurons", in *The Cognitive Neuroscience* Ed. M S Gazzaniga (Cambridge, MA: MIT Press) pp 1021 – 1034

Grush R, 2000 "Self, world and space: The meaning and mechanisms of ego- and allocentric spatial representation" *Brain and Mind* **1** 59 – 92

Hermer L, Spelke S S, 1996 "Modularity and development: the case of spatial reorientation" *Cognition* **61** 195 – 232

Holdstock J S, Mayes A R, Cezayirli E, Isaac C L, Aggleton J P, Roberts N, 2000 "A comparison of egocentric and allocentric spatial memory in a patient with selective hippocampal damage" *Neuropsychologia* **38** 410 – 425

Holmes M C, Sholl M J, 2005 "Allocentric coding of object-to-object relations in overlearned and novel environments" *Journal of Experimental Psychology: Learning, Memory, and Cognition* **31** 1069 – 1087

Jordan K, Schadow J, Wüstenberg T, Heinze H-J, Jäncke L, 2004 "Different cortical activation for subjects using allocentric or egocentric strategies in a virtual navigation task" *NeuroReport* **15** 135 – 140

Klatzky R L, 1998 "Allocentric and egocentric spatial representations: Definitions, distinctions, and interconnections", in *Spatial Cognition: An Interdisciplinary Approach to Representation and Processing of Spatial Knowledge* Lecture Notes in Artificial Intelligence 1404, Eds C Freksa, C Habel, K F Wender (Berlin: Springer) pp 1 – 17

Klatzky R L, 1999 "Path completion after haptic exploration without vision: Implications for haptic spatial representations" *Perception & Psychophysics* **61** 220 – 235

Klatzky R L, Lederman S J, 2003 "Representing spatial location and layout from sparse kinesthetic contacts" *Journal of Experimental Psychology: Human Perception and Performance* **29** 310 – 325

Levelt W J M, 1984 "Some perceptual limitations on talking about space", in *Limits in Perception* Eds A J van Doorn, W A van de Grind, J J Koenderink (Utrecht: VNU Science Press) pp 328 – 358

Mou W, McNamara T P, Valiquette C M, Rump B, 2004 "Allocentric and egocentric updating of spatial memories" *Journal of Experimental Psychology: Learning, Memory, and Cognition* **30** 142 – 157

Nadel L, Hardt O, 2004 "The spatial brain" *Neuropsychology* **18** 473 – 476

Parslow D M, Rose D, Brooks B, Fleminger S, Gray J A, Giampietro V, Brammer M J, Williams S, Gasston D, Andrew C, Vythelingum G N, Ioannou G, Simmons A, Morris R G, 2004 "Allocentric spatial memory activation of the hippocampal formation measured with fMRI" *Neuropsychology* **18** 450 – 461

Pohl W, 1973 "Dissociation of spatial discrimination deficits following frontal and parietal lesions in monkeys" *Journal of Comparative and Physiological Psychology* **82** 227 – 239

Presson C C, DeLange N, Hazelrigg M D, 1989 "Orientation specificity in spatial memory: What makes a path different from a map of a path?" *Journal of Experimental Psychology: Learning, Memory, and Cognition* **15** 887 – 897

Rizzolatti G, Fadiga L, Fogassi L, Gallese V, 1997 "The space around us" *Science* **277** 190 – 191

Semmes J, Weinstein S, Ghent L, Teuber H L, 1963 "Correlates of impaired orientation in personal and extrapersonal space" *Brain* **86** 747 – 772

Shelton A L, Gabrieli J D E, 2004 "Neural correlates of individual differences in spatial learning strategies" *Neuropsychology* **8** 442 – 449

Tipper S P, Lortie C, Bayliss G C, 1992 "Selective reaching: Evidence for action-centered attention" *Journal of Experimental Psychology: Human Perception and Performance* **18** 891 – 905

Tversky B, 1991 "Spatial mental models", in *The Psychology of Learning and Motivation: Advances in Research and Theory* volume 27, Ed. G H Bower (New York: Academic Press) pp 109 – 145

Waller D, Greenauer N, 2007 "The role of body-based sensory information in the acquisition of enduring spatial representations" *Psychological Research* **71** 322 – 332

Waller D, Hodgson E, 2006 "Transient and enduring spatial representations under disorientation and self-rotation" *Journal of Experimental Psychology: Learning, Memory, and Cognition* **32** 867 – 882

Wang R F, Spelke E S, 2000 "Updating egocentric representations in human navigation" *Cognition* **77** 215 – 250

Wexler M, 2003 "Voluntary head movement and allocentric perception of space" *Psychological Science* **14** 340 – 346

Woodin M E, Allport A, 1998 "Independent reference frames in human spatial memory: Body-centered and environment-centered coding in near and far space" *Memory & Cognition* **26** 1109 – 1116

Appendix 1. Coordinates (in cm) for the B and H point staring from the H and S points.

No. of trial	Quadrant	SB	HB	SC	HC	SB + SC	HB + HC
T-I	Q3	40	12	10	38	50	50
T-II	Q1	08	40	42	10	50	50
T-III	Q4	16	20	34	30	50	50
T-IV	Q2	32	28	18	22	50	50
T-V	Q2	28	32	22	18	50	50
T-VI	Q4	20	16	30	34	50	50
T-VII	Q1	12	36	38	14	50	50
T-VIII	Q3	36	08	14	42	50	50
T-IX	Q3	42	14	08	36	50	50
T-X	Q1	10	42	40	08	50	50
T-XI	Q4	18	22	32	28	50	50
T-XII	Q2	34	30	16	20	50	50
T-XIII	Q2	30	34	20	16	50	50
T-XIV	Q4	22	18	28	32	50	50
T-XV	Q1	14	38	36	12	50	50
T-XVI	Q3	38	10	12	40	50	50