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Differential developmental trajectories for egocentric, environmental and intrinsic frames of reference in spatial memory

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Abstract

We studied the development of spatial frames of reference in children aged 3–6 years, who retrieved hidden toys from an array of identical containers bordered by landmarks under four conditions. By moving the child and/or the array between presentation and test, we varied the consistency of the hidden toy with (i) the body, and (ii) the testing room. The toy's position always remained consistent with (iii) the array and bordering landmarks. We found separate, additive performance advantages for consistency with body and room. These effects were already present at 3 years. A striking finding was that the room effect, which implies allocentric representations of the room and/or egocentric representations updated by self-motion, was much stronger in the youngest children than the body effect, which implies purely egocentric representations. Children as young as 3 years therefore had, and greatly favoured, spatial representations that were not purely egocentric. Viewpoint-independent recall based only on the array and bordering landmarks emerged at 5 years. There was no evidence that this later-developing ability, which implies object-referenced (intrinsic) representations, depended on verbal encodings. These findings indicate that core components

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of adult spatial competence, including parallel egocentric and nonegocentric representations of space, are present as early as 3 years. These are supplemented by later-developing object-referenced representations.

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1. Introduction

A well-known distinction exists between two potential frames of reference in spatial memory. Egocentric representations of location, expressing an object's relation to the self, would be simple to generate from sensory data, and could provide a direct basis for action. Allocentric representations, expressing a location with respect to an external frame of reference (e.g. one provided by visual landmarks) would be more difficult to compute, but would provide a better basis for flexible navigation and for the long term storage of complex layouts.

In the present study we trace the developmental time courses of different types of representation using a task in which children recall the locations of hidden toys. A body of developmental literature describes transitions from "egocentric" to "allocentric" responses to stimuli in early childhood (e.g. [Acredolo, 1978](#); [Bremner & Bryant, 1977](#); [Piaget & Inhelder, 1967](#)). Our paradigm takes as its starting point the fact, now well established in the adult and animal literature, that different frames of reference are not mutually exclusive, but ordinarily operate in parallel ([Nadel & Hardt, 2004](#)). In a factorial design, we distinguish between the contributions to performance of those frameworks for representation provided by the body, and those provided by the environment. In this way we are able to provide answers to some questions about the development of viewpoint independence raised, but inconclusively answered, in earlier perspective-taking studies (e.g. [Huttenlocher & Presson, 1973](#); [Piaget & Inhelder, 1967](#)).

Recent studies of adult spatial memory by [Simons & Wang \(1998\)](#); [Wang & Simons \(1999\)](#) have provided an elegant demonstration of the parallel effects of frames of reference defined by (i) the body, and (ii) the surrounding environment. Participants were shown an array of five objects and subsequently asked to say which of the objects had been moved. Between presentation and test, the participant's position and the array's orientation within the room were manipulated so that the array of objects remained either consistent or inconsistent with its initial position, as judged relative to (i) the body and (ii) the room. In the baseline condition, where both frames of reference were available, participants were tested from the same place in the room and the array did not move. When they moved to a new place in the room, and therefore saw a new view of the array, the body-array relation was made inconsistent. The room-array relation was made inconsistent when participants moved to a new place, but the array was simultaneously rotated so that their view of it matched the view seen at the start. Finally, when the array was rotated but participants answered from the same place in the room, both relations were made inconsistent. Simons and Wang's results showed that the frames of reference provided by body and environment had additive effects on recall accuracy. Recall was most accurate

when both were consistent between presentation and test, and least accurate when neither was consistent. This paradigm provides the basis for our developmental study.

The first result from Simons and Wang's work was improved performance when the array did not move within the surrounding room. For example, participants who moved to a new viewing position performed better than those who experienced the equivalent viewpoint change when it was produced by rotation of the array. In an illuminated testing room, this advantage could be explained by two different effects. First, accuracy could be improved by allocentric representations of the objects' locations within the surrounding framework of visual cues. Array rotation would disrupt these relationships. Second, participants who walked to a new position had the advantage of self-motion cues, including those from the vestibular sense and from motor-efference, to the distance and direction of their displacement. These cues could be used for "internal updating" of the object locations.

Spatial updating processes, including *path integration* and *dead reckoning*, are found in many species, including humans (Farrell & Robertson, 1998; Loomis, Klatzky, Golledge, Cicinelli, Pellegrino and Fry, 1993; Mittelstaedt & Mittelstaedt, 1980). Simons & Wang (1998) argued that spatial updating was sufficient to explain the room-consistency effect, since it was still found in a darkened room, where no landmarks external to the array were visible. In a subsequent study, Burgess, Spiers, and Paleologou (2004) separated effects of spatial updating from use of an allocentric reference frame by additionally varying the array's consistency with an external landmark. They found performance advantages both for consistency with movement cues and for consistency with the landmark, showing that subjects used both spatial updating from self-motion cues and allocentric representations of location relative to an external landmark.

The second result from Simons and Wang's work was an advantage for consistency with the body: participants were more accurate when they viewed the array from the same angle at presentation and test. The availability of a familiar view would make it possible to recall the layout using egocentric representations such as stored visual images. Advantages for recall from familiar viewpoints are reported in species ranging from ants to humans (Diwadkar & McNamara, 1997; Judd & Collett, 1998; Roskos-Ewoldsen, McNamara, Shelton, & Carr, 1998). The Simons and Wang paradigm is innovative in allowing the comparison of body-consistency and room-consistency effects within the same task.

A final result was that when none of the frames of reference provided by body or environment were consistent between presentation and test, accuracy was still far above chance. In this condition, produced by rotating the array while keeping the participant in the same place in the room, the only frame of reference that remained consistent was provided by the array itself. This type of allocentric frame of reference, also referred to as an *intrinsic* reference frame (Levinson, 2003), was defined by the array's layout and overall shape. An allocentric representation providing a viewpoint-independent map of the array's layout would account for participants' ability to solve the task. Alternatively, participants could mentally rotate the array and match it to a stored visual image. The task does not distinguish between these possibilities, but common to both is the requirement to adopt a frame of reference intrinsic to the array, distinct from those defined by the observer or the testing space.

To summarise, the array rotation paradigm provides measures of a range of different representations in spatial memory. In the present study, we collected developmental data with a modified version of the task. Questions about the development of spatial representations are by no means new, but this task's factorial design makes it possible to distinguish between them in novel ways. In the "perspective problem" studies of [Piaget & Inhelder \(1967\)](#); [Huttenlocher & Presson \(1973\)](#), children imagined taking a different perspective with respect to a spatial layout and used models or diagrams to indicate what they would see. These tasks were interesting because they required participants to retrieve layouts in a viewpoint-independent manner, e.g. using allocentric representations. They proved difficult, and were not solved until around 10 years. However, it is likely that this did not only reflect difficulties with forming viewpoint-independent representations. The high rates of "egocentric" responses, in which children made the error of reporting what they could actually see, suggest that an additional component of these tasks was the need to suppress one's own perspective, and, in most tests, to understand what was meant by the instruction to adopt another's viewpoint. The response, selecting a diagram, may also have been difficult, and later studies confirmed that children asked to imagine being at a different side of a spatial array performed much better given questions about parts of the array itself than pictorial stimuli ([Newcombe & Huttenlocher, 1992](#)).

Our task extends more recent studies by [Huttenlocher, Newcombe, and Sandberg \(1994\)](#); [Newcombe, Huttenlocher, Bullock Drummey, and Wiley \(1998\)](#), in which children searched for toys after seeing them buried in a sandbox. In the 1994 study, systematic biases provided evidence for encodings with respect to the edges of the box at 16–24 months. In the 1998 study, children aged 16–36 months searched after walking to the opposite side of the box, a manipulation that eliminated the egocentric frame of reference. Visual cues in the testing room were either visible, or hidden by a screen. All age groups searched accurately from the opposite side, and after 22 months performance improved when the additional room cues were visible, a result consistent with accurate spatial updating in younger children, and emergence of allocentric representations using distal landmarks at 22 months. Children who walked around and searched from a new position were also less accurate than those in the 1994 study who had searched from the same place, implying an advantage for representations made available by an egocentric frame of reference. The view-change condition however entailed an additional walking task, which children who answered from the same place did not have. The difference between these conditions could therefore partly reflect disruption from this secondary task. Finally, although the gaze of participants was broken between presentation and test, it is not apparent that children were prevented from refixating the hiding place and tracking it while walking around the array, so keeping it perceptually available. It would be ideal to rule out such strategies completely for a test of spatial representations that do not depend solely on the momentary retinal input.

The adult task of [Simons and Wang](#) avoided both of these difficulties. The walking demand was matched across conditions, so that participants responding from the same position walked the same distance between presentation and test as those responding from the other position; to do this, they walked halfway to the other position and back. Fixation of the array during the interval was not possible because it was only viewable at the two test positions. The present study adopted these features of the array rotation paradigm, as

well as its factorial design. Instead of a change detection task, which might not be so easily comprehensible to children, it took the form of a search task with hidden toys. On each trial the child had to recall the position of a single toy hidden in one of 12 identical containers bordered by distinctive landmarks, from the same or from a different position, after rotation or no rotation of the whole array, including these local landmarks. All participants experienced all conditions. The age range we tested was 3–6 years.

The condition in which children walked to a new place replicates standard tests of retrieval from a new viewpoint with both environment and movement cues available (e.g. Newcombe et al., 1998). When viewpoint changes were produced by array rotation rather than self-motion, the solution depended only on visual cues intrinsic to the array, including its overall shape and the landmarks fixed at two of its edges. This condition constituted the test for viewpoint-independent recall. Two further conditions—a baseline condition in which children answered from the same place, and a condition in which they walked but the array was also rotated so that the same view was presented—completed the factorial design. Since conditions were matched for the attentional and motor demands of walking, differences between them can be interpreted as direct effects of the spatial manipulations.

Viewpoint-independent retrieval could depend on something other than allocentric spatial representations. One possibility is that it depends on the ability to form verbal representations of the hiding places. A final trial on which a verbal description of the hiding place was elicited, without warning and when the array was not visible, measured the extent to which children's representations of the hiding places were verbally mediated.

2. Method

2.1. Subjects

Participants were children at London primary schools and nurseries, and volunteers at the Department of Psychology, University College London. We tested 73 children: 18 three-year-olds (mean age 3.5, SD 0.25 years; 9 male), 21 four-year-olds (mean age 4.5, SD 0.26 years; 11 male), 17 five-year-olds (mean age 5.5, SD 0.30 years; 8 male) and 17 six-year-olds (mean age 6.5, SD 0.35 years; 9 male). The mean ages of males and females did not differ overall ($P > 0.9$), nor did they differ within any age group (for all groups, $P > 0.4$). All parents gave consent for their child's participation in the study, in line with the relevant Ethics Committees.

2.2. Apparatus

The test apparatus (Fig. 1a) comprised a dark green board measuring 82 cm × 82 cm. A portion of the board (70 cm × 70 cm) was taken up by an array of 12 identical inverted white cups (diameter 8 cm) arranged in a fixed pattern which avoided the appearance of a grid or other distinctive figure. Toy houses and animals which could serve as landmarks were arranged in the remaining space, occupying two of the board's edges. More distant uncontrolled visual cues, which were fixed and therefore could not provide a basis for retrieval when the array was rotated, were also present in the testing room. Two viewing positions were marked on the floor, 20 cm from two adjacent edges of the board. The line of sight of each was

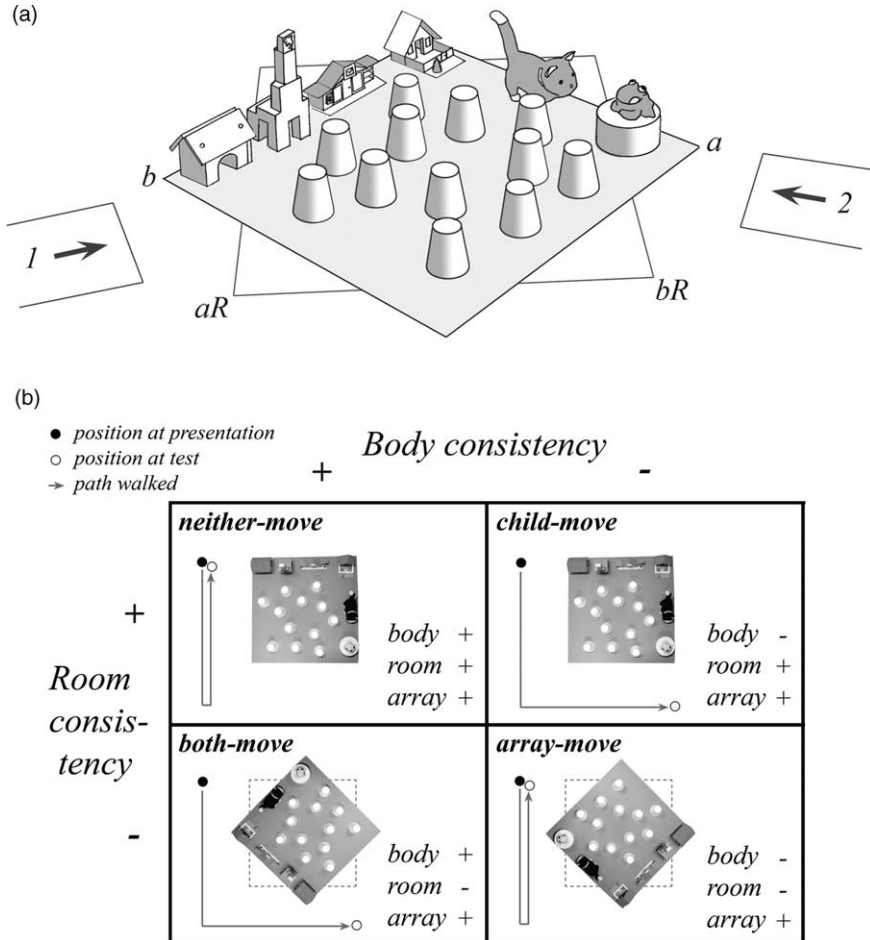


Fig. 1. The apparatus (a). After the toy was hidden, changes in the hiding place's relation to the *body* (i.e. changes in the angle at which participants viewed the array) were obtained either by walking the child to a new position (*child-move* condition; e.g. walk from 1–2), or by rotating the board (*array-move* condition; e.g. board rotates *a* to *aR* while participant walks from 1 halfway to 2, and back to 1). When participant position changed and the board rotated (*both-move* condition), the original *body* relation (viewing angle) was matched (e.g. subject walks 1–2 while board rotates *b* to *bR*). In the baseline *neither-move* condition, the child walked halfway to the other position and back and the board was not rotated. These four conditions (b) systematically varied the hiding place's consistency with the *body* and the *room*. The frame of reference provided by the *array* itself was always consistent between presentation and test. This frame of reference provided the only basis for correct retrieval in the *array-move* condition.

22.5° from the normal to the nearest edge. The view of the array was therefore shifted by 135° between the two positions. A line which participants walked between hiding and retrieval was also marked on the floor. The stimuli whose hiding places had to be recalled were small attractive toys.

2.3. Design

Subject movement and array rotation varied according to a 2×2 design with the factors *body consistency* and *room consistency*. Before retrieval, children either walked to the other viewing position, or halfway and back to their initial position. At the same time, the array was either rotated by 135° relative to the room, or was not rotated. When the child walked around and the array rotated, the hiding place remained consistent with the body—that is, the original view of the array was matched. The conditions in the experiment are described in detail in Fig. 1a and b. Note that the two factors state the hiding place's consistency with *body* and *room* respectively, but neither states the participant's absolute position in the testing room. In this respect our description of the 2×2 design differs from that in Wang & Simons (1999), although it embodies the same four conditions. The frame of reference defined by the *array* itself was always consistent between presentation and test. In the *array-move* condition this provided the only basis for correct retrieval.

Participants completed four blocks of four trials, each block comprising one trial from every condition. Condition orders and hiding locations were selected in sequences pseudo-randomly generated for each child. The cup near the centre of the board was never used because it was not sufficiently displaced by rotation (see *Analysis*). The remaining 11 locations appeared at least once for each participant, but the same location was not repeated on successive trials, and locations in different regions of the board (landmark-adjacent, centre, edge) appeared with equal frequency in different conditions.

Since children in our pilot study were most motivated to look for toys at the very start of the task, no practice trials were included. However conditions in the first block had a constant order (*neither-move*, *child-move*, *array-move*, *both-move*), which introduced all participants consistently to the different demands of the task. Condition orders within the following three blocks were random. On each trial we recorded the first location searched. This was subsequently converted to distance (cm) from the correct cup and a standard performance score scaled against chance (see *Analysis*). On a final trial following the four blocks of four, a verbal description of the hiding place was elicited; the hiding location for this trial was constant for all participants.

2.4. Procedure

One experimenter hid toys and recorded responses while a second walked with the child. On each trial a different toy was hidden. The first experimenter interested the participant in the stimulus by asking what it was: this attracted their attention and helped to establish interaction with shy children. Identification of the toy (e.g. a teddy, a pig, a dinosaur) met with enthusiasm from the experimenters, who praised success generously in order to counteract the potentially demotivating effect of failing to find the toys.

The first experimenter picked up one of the cups and set the toy down in the space under it. While the cup was still held in the air, the experimenters checked that the participant was attending to the position of the toy by asking a question, for example “can you see where he's hiding?”. The cup was lowered once the experimenters were sure that the child had seen the toy. The second experimenter then walked the participant either all the way around to the other viewing position, or halfway and back. A large sheet of card was held

to one side of the child's face to block their view of the array during the entire walking phase. Both experimenters monitored the child's gaze, and those who tried to look past the card were warned not to "peek" and encouraged to look up at the experimenter who was walking with them instead. On the *room inconsistent* conditions (*both-move* and *array-move*) the first experimenter additionally rotated the board during this part of the trial.

In the search phase both experimenters directed their gaze at the participant rather than at any part of the array. Children were asked to use a ruler to tap the top of the cup where the toy was hiding, and an experimenter lifted the cup. By preventing children from lifting cups by themselves, a process hard to regulate once allowed to get underway, we emphasised the importance of recalling the right cup rather than using trial and error.

On the first occasion when rotation occurred, the experimenters carefully demonstrated how the board could be turned before the trial began. On all rotation trials, children were warned before they searched that the array had "turned around". These measures were motivated by the finding in our pilot study that younger children tended to search as if the rotation had not occurred. We wanted to counter the possibility that any child was unaware that a manipulation of the board had taken place. On all trials other than the first rotation trial, children did not know where they would be walking, and whether the array would be rotated or not, until the toy had been hidden and the walking phase had started. Each trial began at whichever viewing position the last had ended. The even distribution of same position and different position trials meant that on average the two viewpoints were experienced equally often.

On a final trial the toy was always hidden under the same cup. This location admits a variety of correct verbal descriptions, but is uniquely specified by its relation to two landmarks, "between the cat and the frog" (see Fig. 1a). Participants were not given advance warning that this trial would differ from the others. However after the toy was hidden, the second experimenter turned the child away from the array and, blocking their view with the card, asked: "can you *tell* me where [the toy] is hiding?" For children who did not answer or tried to point, the question was repeated in different ways ("can you *say* to me where it is?"). Answers were recorded verbatim.

2.5. Analysis

Our dependent measure, first cup searched, was initially converted to a distance (cm) from the correct cup, 0 cm indicating a correct search. For each trial this error distance was transformed into a standardised performance score as follows. Each hiding place has an associated average error expected by chance. This value, which would be obtained by a participant searching at random over many trials, is given by the mean of the distances between that place and all 12 possible search locations, including the correct one, and varies from location to location¹. Performance scores were calculated with the formula $100 \times (\text{chance distance} - \text{error distance}) / \text{chance distance}$. The effect of this transformation is that 100 corresponds to a correct search, while 0 corresponds to a search at a distance

¹ The values range from 23.1 to 33.8 cm, with mean 29.0 cm (SD 3.7 cm).

equal to chance. A value below 0 corresponds to a search error greater than the average expected by chance.

A participant's overall performance score for each condition was calculated as the mean of their scores in that condition. Each participant thus contributed four mean performance scores, one for each condition, to this part of the analysis. A repeated measures ANOVA was carried out with within-subjects factors *body consistency* and *room consistency* (see Fig. 1b), and between-subjects factors *age group* and *gender*.

The analysis described so far measures performance on each trial as a distance between correct location and chance. However, the correct location is not the only place at which we might hypothesise that searches will consistently occur. In fact, on three of our conditions, the use of a frame of reference incorrect for the condition would predict a search at a specific incorrect location. An example of this is provided by younger children in our pilot study, who searched, in the *array-move* condition, close to the place where the toy had been before board rotation took place. This indicates either ignorance of our manipulation, which in this study we have sought to rule out (see *Procedure*), or an incorrect choice of frames of reference. In this condition, the frames of reference defined by *body* and *room* both specify the same, incorrect location (see Fig. 1b).

Accordingly in the *array-move* condition, the place specified by these frames of reference, which corresponds to the place occupied by the toy before rotation, was taken as the origin for a second calculation of "performance score". Since no cup precisely occupies the place of another following rotation, it is not possible to obtain a score of 100 (search error 0 cm) on this measure. Nevertheless we can determine whether searches at any age were closer to the hypothesised place than would be expected by chance.

Similarly, in the *both-move* condition, a second hypothesised location for search was the place correct with respect to a frame of reference defined by the *room*, i.e. the toy's initial place before rotation. A search at this location would suggest that this frame of reference was used in preference to those defined by *body* and *array*. In the *child-move* condition, a possible second location for search was the place initially correct with respect to the *body*. Searching close to here would constitute the classic "egocentric" error seen in very young children, who search after movement as if they have not moved (e.g. Acredolo, 1978). Since the children in this study were much older than those reported to make the egocentric error, we did not expect to see this pattern.

The relationship between each "alternative hypothesis" performance measure and the main performance measure is such that a score above chance on one usually equates to a score below chance on the other. This is a function of the magnitude of the view difference, 135°, which displaces cups (apart from the unused centre location) considerably from their original positions. There is a strong negative correlation between the main performance measure and the alternative performance measure; e.g. for all combinations of hiding and search locations on the *array-move* condition, $r = -0.46$.

A further analysis was more exploratory. We were interested to see whether some locations were better remembered than others. An ANOVA was carried out on performance scores from all trials, with the factors *location* (1–11), *body consistency*, and *room consistency*. Since the total number of trials per location was limited, these data were not suitable for further subdivision by age or gender. Neither was the experiment designed to balance the many possible factors influencing ease of recall. Even so, we

considered that any variations in performance as a function of hiding place would be of interest.

A final analysis examined answers on the unexpected verbal trial. The logic of the test was this: a child who was mentally rehearsing a phrase would most likely produce the phrase in response to our question. On the other hand, a child who was not using a verbal strategy could likewise produce the phrase by describing a mental image. In other words, the use of a verbal strategy was a sufficient but not a necessary condition for a correct verbal description. We therefore took failure to describe the location to be good evidence for the absence of a verbal strategy, but success to be equivocal.

3. Results

Mean performance scores by age group are plotted in Fig. 2a. The same order of condition difficulty (*neither-move*, *child-move*, *both-move*, *array-move*) is evident at every age, and matches the pattern of adult performance on the change detection task of Wang and Simons (Fig. 2c). This pattern is consistent with the decreasing availability of different

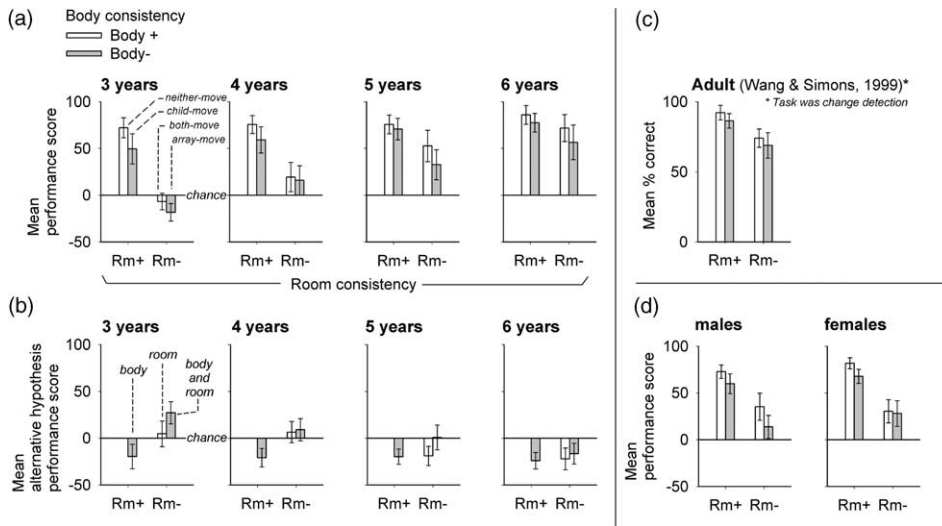


Fig. 2. Mean performance scores and 95% confidence intervals by age and condition (a). White bars: *body* frame of reference consistent between presentation and test. Grey bars: *body* frame of reference inconsistent. Columns on the left: *room* frame of reference consistent between presentation and test. Columns on the right: *room* frame of reference inconsistent. The order of conditions, left to right, is therefore *neither-move*, *child-move*, *both-move*, *array-move*, as labelled in the age 3 plot. For the latter three conditions, “alternative hypothesis” performance scores are plotted (b), based on the distances of searches from places predicted by the use of those frames of reference that are incorrect in the context of each condition. These incorrect places are specified by the *body* (*child-move* condition), the *room* (*both-move* condition), and both *body* and *room* (*array-move* condition), as labelled in the age 3 plot. No frame of reference predicts an incorrect location for the *neither-move* condition. (c) replots adult results from Wang & Simons (1999). (d) plots mean performance scores for males and females.

frames of reference across conditions (see Fig. 1b): *neither-move* (body + room + array) > *child-move* (room + array) > *both-move* (body + array) > *array-move* (array). The 95% confidence intervals show that mean performance on *both-move* was not significantly above chance until 4 years, while performance on *array-move* was not above chance until 5 years. Groups of children aged 5 and 6 years were therefore above chance at recalling from a novel viewpoint a location indicated only by spatial relations intrinsic to the array, i.e. the relative positions of landmarks and cups.

There were main within-subjects effects for *body consistency* ($F(1, 65)=31.1, P<0.001$) and *room consistency* ($F(1, 65)=159.8, P<0.001$), but there was no interaction between these factors ($P>0.9$). The between-subjects factor *age* was significant ($F(3)=24.3, P<0.001$); there was a significant interaction between *age* and *room consistency* ($F(3, 65)=12.2, P<0.001$), but no interaction between *age* and *body consistency* ($P>0.6$). The three-way interaction between *age*, *body* and *room consistency* was not significant ($P>0.1$).

These results show that performance was improved by consistency with both the frames of reference provided by the body and the environment. These two factors did not interact, but were additive. The effect of consistency with the *room* changed significantly over the age range we studied (significant interaction *room consistency* \times *age*), while the effect of consistency with the *body* did not (no significant interaction *body consistency* \times *age*). These results are evident in Fig. 2a: the difference between bars on the left (*room* consistent) and bars on the right (*room* inconsistent) reduced with age. At the same time, the difference between white (*body* consistent) and grey (*body* inconsistent) bars was quite constant across ages. It is striking that the effect of *room consistency* was much greater than the effect of *body consistency* for the youngest children. The absence of a significant three-way interaction between *body* and *room consistency* and *age* reflects the regularity with which the *body* and *room* factors combined in all age groups.

The 95% confidence interval for the *array-move* condition at age 3 shows that performance was significantly *below* chance. That is, three-year-olds searched further from the correct location than would participants searching at random, which implies the consistent use of an incorrect strategy. Our alternative hypothesis measure for this condition predicted searches close to the place initially correct with respect to both *body* and *room*. The proximity of searches to this location, compared with the distance expected by chance is plotted in Fig. 2b. For the *array-move* condition (grey bar on the right) at age 3, searches were significantly closer to this place than chance. Thus when faced with a rotation of the array and a novel view of it, three-year-olds' searches were consistent with the frames of reference provided by *body* and *room*, whereas correct retrieval would entail disregarding these and using only the frame of reference intrinsic to the *array*. The mean proximity of search to this incorrect location fell steadily with age, and was not above chance for any age group above 3. Searches on the *both-move* condition were not significantly closer than chance to the location predicted by the incorrect use of a *room* frame of reference at any age (Fig. 2b, white bar on the right).

When the array was not moved, the *room* frame of reference specified the correct location for search. Our *child-move* condition replicates previous tests of retrieval after walking to a new viewpoint (e.g. Newcombe et al., 1998). Performance on this condition improved with age (Fig. 2a, grey bars on the left). To determine whether the improvement

was significant, we analysed mean *child-move* performance scores in a one-way ANOVA with the factor *age*. The effect of *age* was significant ($F(3)=3.64, P<0.02$). Thus between 3 and 6 years, accuracy improved on the classic task of retrieving a hidden object after walking to a novel viewpoint. The alternative search location predicted for the *child-move* condition was the place initially correct with respect to the *body*. In every age group, searches were significantly further from this place than chance (Fig. 2b, grey column on the left). This confirms that even the youngest group in our sample did not make the classic “egocentric” error on this condition, but took their change of position into account when they searched.

Performance on the baseline *neither-move* condition (Fig. 2a, white column on the left) showed a small, nonsignificant improvement with age ($F(3)=1.47, P>0.2$). Since mean scores were not close to our measurement ceiling (score 100), this does not seem to be the limiting factor. Rather, with all frames of reference available, recall for a single object among 12 locations was already good at 3 years, but those limitations of accuracy (and perhaps continuous attention to the task) which kept it below ceiling were still in place at age 6.

3.1. Effects of gender

The between-subjects factor *gender* was not significant alone ($P>0.1$), but only in a three-way interaction with *body consistency* and *room consistency* ($F(1, 65)=4.8, P<0.05$). This interaction is plotted in Fig. 2d. Females were better on all conditions except *both-move*, and showed a particularly large advantage on the *array-move* condition. Males were much less accurate on *array-move* than on *both-move*, whereas females’ performance on these conditions was similar. Although females were (nonsignificantly) better overall, it is interesting that the *gender* interaction does not simply imply a faster overall development for the females.

3.2. Performance by hiding location

An ANOVA with factors *location*, *body consistency* and *room consistency* found a main effect of *location* ($F(10)=2.2, P<0.02$), an interaction between *location* and *room consistency* ($F(10)=2.1, P<0.03$), but no interaction between *location* and *body consistency* ($P>0.3$), and no three-way interaction between these factors ($P>0.2$). Fig. 3 plots mean performance scores as a function of hiding location and *room consistency*. The interaction is evident mainly in that choice of hiding location had greater effects on performance when the *room* frame of reference was inconsistent.

In both *room consistent* and *inconsistent* conditions, the places recalled with least accuracy were near the centre of the array and far from any landmarks. Immediate proximity to a landmark was helpful, but not necessary for a high rate of correct retrieval: the corner cup (bottom right, Fig. 3) was well remembered, particularly in the *room inconsistent* conditions. The corner of the board may have served as a landmark, but it is also likely that this cup’s distinctive position in the layout of the array made it memorable. It is also true that positions at the edge of the array have fewer nearby alternatives than those in the middle.

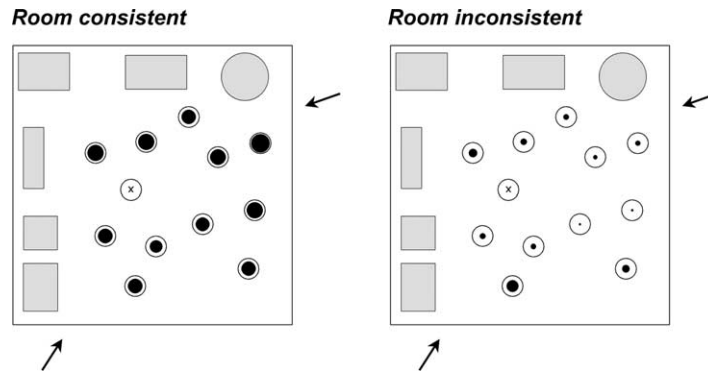


Fig. 3. Mean performance scores by location on *room consistent* conditions (left) and *room inconsistent* conditions (right). The array is shown from above, with landmarks (grey), cups (white circles) and the two viewing angles (arrows). Diameters of black circles correspond to mean performance scores. The scale ranges from no black circle (mean score 0), to the edge of the cup (mean score 100). “x” marks the cup which was never used.

3.3. Verbal descriptions

Only 3 children, all aged 6, mentioned both the cat and the frog in response to our surprise question on the final trial. Descriptions mentioning either landmark were more common—examples included “near the cat”, “beside the cat”, “next to the frog”. Although these might not suffice to describe the location unambiguously to a third party (see Fig. 1a), they could be a basis for retrieval in a participant who understood them in a particular way. We therefore scored answers that referred to either landmark as correct descriptions. There were no correct descriptions at age 3, four at age 4, five at age 5, and 12 at age 6. As percentages of children in each age group, these were 0, 19, 29 and 71%. Other children tended either to give no response, or to give nonspecific answers (“over there”; “in the cup”).

To check whether the emergence of viewpoint-independent recall at 5 years could have depended on verbal encodings, we examined performance on the *array-move* condition of those five-year-olds who did not mention either landmark in response to the surprise question ($n = 12$; mean age 5.4 years, SD 0.27). The performance of these children was above chance at the 5% level (mean score 21.9 with 95% c.i. 19.4). Thus even those five-year-olds who could not produce a verbal representation of this hiding place demonstrated viewpoint-independent recall in the absence of those frames of reference provided by *body* or *room*.

4. Discussion

Between the ages of 3 and 6 years, three distinct frames of reference facilitated memory for locations in our array. There was a significant effect for consistency of the target with (i) the *body*. The *body* frame of reference was available in the conditions *neither-move* and

both-move. Its effect is evident in advantages for *neither-move* over *child-move*, and *both-move* over *array-move* (see Fig. 2a). Consistency with the *body* would allow the use of egocentric representations that are not updated with movement, such as stored visual images. Those representations that facilitated performance when the *body* relation was held constant were already developed by 3 years, and did not undergo significant changes through age 6.

There was a further effect for consistency with (ii) the *room*. The *room* frame of reference was available in the conditions *neither-move* and *child-move*, and its effect can be seen in advantages for *neither-move* over *both-move*, and *child-move* over *array-move* (Fig. 2a). Like the *body* effect, the *room* effect was already present at 3 years. The striking result was that at this early age, it was much greater than the *body* effect (see Fig. 2a, and F values above): the array's position within the external reference frame of the room influenced the youngest subjects much more than its position within the egocentric reference frame defined by the body. This large *room consistent* advantage in performance in the youngest children must have depended on representations that are not purely egocentric—i.e. those taking external space into account, whether through landmark use or spatial updating. This result shows that any spatial “egocentrism” in infancy had definitively disappeared by 3 years, at which age children showed a strong awareness of their movement within the surroundings. When the toy's position within the room was changed, but purely egocentric retrieval remained possible because the body relation was kept constant (*both-move* condition), performance at 3 years was at chance, whereas in a young “egocentric” infant good performance would be expected from a comparable condition. The *room* effect diminished over the age range (as performance in the room-inconsistent *array-move* and *both-move* conditions improved), but was still present at age 6. An ANOVA with only those children aged 6 confirms that the effects of both *body* and *room* were still significant at this age.

The factors (i) *body* and (ii) *room consistency* did not interact, showing that when both frames of reference were present their effects were additive. The order of condition difficulty in every age group, which was consistent with the availability of these frames of reference, matched the pattern found in adults on a similar task (Wang & Simons, 1999). The consistency with which this additive pattern occurred across the age range meant that there was no significant three-way interaction between these two factors and *age*.

Performance on the conditions *both-move* and *array-move*, which were not consistent with the *room*, (Fig. 2a, bars on the right), steadily caught up with performance on the conditions that were consistent (bars on the left). This age trend was the result of two separate effects. First, when neither of the frames of reference provided by *body* or *room* indicated the correct location (*array-move* condition), the youngest children nevertheless searched consistently with these (Fig. 2b). As a result their performance was very low; indeed at 3 years searches were further from the correct places than would be expected by chance. However, performance on this condition rose significantly above chance at 5 years. Simply ignoring those frames of reference that were incorrect for this condition would have sufficed to bring performance to, but not beyond, chance. To perform above chance, the five and six-year-old groups must have used some further frame of reference to solve the task. The only frame of reference that remained stable with respect to the target in the *array-move* condition was provided by (iii) the array itself, i.e. an “intrinsic” frame

of reference (Levinson, 2003). Children aged 5 and 6 years must have developed the ability to retrieve objects using only those visual cues present in the array. These included the landmarks around two of its edges, as well as the edges themselves and the configuration of hiding places (cups).

Developmental changes in the use of the *room* frame of reference therefore reflected its replacement by the more appropriate *array* frame of reference in older children. For this reason, these results do not indicate whether or how much the *room* frame of reference became used more effectively with age. It is striking however that use of the *room* frame of reference was already present at 3 years, and that it was so privileged over the *body* frame of reference at this young age.

The emergence of viewpoint-independent retrieval at 5 years in the present study was much earlier than reported in the classic perspective-taking studies of Piaget & Inhelder (1967); Huttenlocher & Presson (1973), where the transitional age was around ten. Our results are consistent with Newcombe & Huttenlocher (1992), who found greatly improved performance when responses were directed at the spatial array itself, rather than at a diagram. In their study, three-year-olds were above chance at indicating, from an (imaginary) novel viewpoint, the positions of objects which did not move within the room between presentation and test (allowing use of a *room* frame of reference), and whose places within the array were constant throughout (allowing children to learn the places incrementally over the course of the experiment). In our study, five-year-olds were above chance at retrieving locations that moved with respect to both body and room between presentation and test, and that changed from trial to trial. These results provide evidence for viewpoint-independent retrieval based only on spatial relations intrinsic to the array at 5 years.

Children in our study were not instructed to solve the task by imagining a perspective change. It has been argued that imaginary perspective changes are difficult because they entail a conflict between the participant's real position and the imaginary position. However in our task, the condition that tested for viewpoint independence (*array-move*) included an analogous conflict. Children had to inhibit responses based on the frames of reference provided by *body* and *room*, and there was evidence in the youngest children's errors for a failure to do this. An inhibition process may therefore be an additional component of our task. We therefore take our task to be a conservative indicator of the emergence of viewpoint-independent retrieval of intrinsic spatial relations, which may be present even earlier than measured here.

We now turn to possible explanations for the emergence of this ability. It could be explained by verbal representations, imaginary rotation, or allocentric ("intrinsic") representations of the hidden toys' places within the array. Our surprise question showed that those five-year-olds who could not produce a verbal description of the hiding place were still above chance at viewpoint-independent recall. There was therefore no evidence that viewpoint-independent recall depended on verbal representations. This conclusion is based on a cautious criterion for identifying possible verbal strategies, which we biased towards detecting "false positives". We used one of the most easily described locations, asked the question at the end, which allowed time for any strategy to develop, and scored descriptions "correct" on a generous criterion. Our reanalysis confirmed viewpoint-independent recall when we excluded all five-year-olds who gave such a description, even

though these descriptions could have been provided by children who were describing mental images, and not pursuing a verbal strategy.

The other two possibilities are less easy to distinguish from our measures. One account is that children adopted the strategies, explicitly required in Piaget's and Huttenlocher's tasks, of mentally translating the current view of the array into a different one. On the alternative account, children developed the capacity to represent locations with respect to the landmarks and other visual features within the array. That is, they encoded locations on an internal "map" of the array, which enabled them to retrieve these directly from novel viewpoints. A result that bears on this question is the effect of hiding location (Fig. 3). The interaction between *location* and *room consistency* corresponds to greater differences across locations on the *room* inconsistent conditions, including the condition *array-move* which provides the test for viewpoint-independent recall. On these conditions, locations that were neither close to a landmark, nor at a distinctive place in the array's shape were recalled with least accuracy (Fig. 3, right). This pattern is consistent with an encoding that represents array locations with respect to local landmarks and overall shape. The same pattern would not obviously be predicted by mental rotation. If mental rotation did take place, then it is surprising that locations at the array's edges, which would have to travel furthest, were subject to less error than those near its centre. This pattern gives some reason to favour the hypothesis that viewpoint independent recall in these children corresponded to an emerging ability to represent locations with respect to local visual cues, but this conclusion remains tentative. Some kind of piecemeal mental rotation using landmarks as local anchor points would represent a compromise between these accounts, and would be consistent with our data.

We have hypothesised that children used direct retrieval from intrinsic (array referenced) representations on our task, whereas mental rotation was one of the requirements that made the classic perspective change studies difficult. These arguments make a testable prediction, which is that if we compared children on the same task, those given a free choice of strategy would perform better than those instructed to use imaginary perspective changes. If retrieval depended on imaginary perspective changes, we would expect the opposite pattern, an immediate clue to the correct solution conferring an advantage on the "perspective change instruction" group.

Consistency with *body* and *room* had different effects on males and females aged 3 to 6. Females outperformed males on every condition but *both-move* (Fig. 2d). Their performance on this condition and on *array-move* was very similar, whereas males' performance on *array-move* was much poorer. Females in this age range were therefore better at using an array centred frame of reference, needed to solve the *array-move* condition, but showed little improvement resulting from additional consistency with the *body* in the condition *both-move*. The female advantage on the baseline (*neither-move*) condition is consistent with results from adult change detection without a change of viewpoint (McBurney, Gaulin, Devineni, & Adams, 1997). Interestingly gender differences for the other conditions differed from those in a comparable adult array rotation task (Burgess et al., 2004), where a significant interaction with gender again corresponded to an overall advantage for females, but this (adult) female advantage included the *both-move* condition but not the *participant-move* condition. The pattern giving rise to a significant interaction in the present study was opposite for two of these

conditions: three to six-year-old females performed better than males on *child-move*, but less well on *both-move*. These differences suggest that rates of development for the use of different frames of reference differ for males and females. Such developmental differences across the age range we studied did not produce any significant interactions involving *gender* and *age*, although the four-way interaction between *gender*, *age*, *body* and *room consistency* approached significance ($p=0.07$). The trends evident in this interaction were consistent with differential rates of development eventually giving rise to the adult pattern.

The *child-move* condition corresponds to a standard test of recall from a novel viewpoint. Although performance was already good at 3 years, it continued to improve significantly through age 6. By contrast, the baseline same viewpoint (*neither-move*) condition showed small improvements which did not reach significance. Since mean scores did not reach measurement ceiling, this effect seems to represent a genuine performance ceiling for this age range. This could indicate attentional or motivational limitations, adding to the data a degree of noise which is relatively constant for ages 3–6 years.

We have proposed that spatial frames of reference in this study influenced performance because they varied which representations were available for children to use. Results from functional neuroimaging and electrophysiological recording increasingly identify such representations with separate neural substrates. A strong possibility is that the developmental changes in spatial behaviour reported here reflect the maturation of separate brain systems, which represent spatial information using different frames of reference. We can identify possible neural correlates for the most important findings from this study, namely the early awareness of hiding places' relation to both body and room at 3 years, the initial dominance of the room, and the emergence of purely viewpoint-independent recall at age 5.

The early-developing *body* advantage implies “purely egocentric” representations, i.e. those not updated by self-motion. “Purely egocentric” responses in very young children are often identified with motor plans, dependent on the dorsal visual stream and posterior parietal cortex (Milner & Goodale, 1995). The early use of the *room* in the present task however suggests that any such motor plans were not purely egocentric, but were updated by self-motion even at the youngest ages. More likely candidates for “purely egocentric” representations are stored visual scenes, dependent on the ventral visual stream and inferotemporal cortex (Milner & Goodale, 1995). Adult imaging and neurorecording indicates viewpoint-dependent representations of visual scenes specifically in parahippocampal cortex (Ekstrom, Kahana, Caplan, Fields, Isham and Newman, 2003; Epstein, Graham, & Downing, 2003).

The similarly early-developing and initially stronger *room* advantage may depend on posterior parietal representations that are body-referenced, but updated by self-motion (Bremmer, Duhamel, Ben Hamed, & Graf, 1997; Colby, 1999). The initial dominance of these over egocentric representations such as visual scenes could represent an early bias for “sensorimotor” (dorsal-stream) over “cognitive” (ventral-stream) representations of space (Rosetti, 1998). Interestingly, early perceptual processing in the lower levels of the dorsal and ventral streams shows no such dorsal-stream advantage; indeed ventral-stream judgments mature more rapidly (Braddick, Atkinson, & Wattam-Bell, 2003). Therefore if the early dominance of the *room* frame of reference does reflect a preference for

dorsal-stream representations, this may depend on a subsequent selection process (or differential timing in the two pathways) rather than the processing capabilities of the dorsal and ventral streams themselves. The strong *room* effect is also consistent with early use of visual landmarks external to the array. An adult array rotation study which distinguished landmark use from spatial updating by moving an external landmark relative to the participant (Burgess et al., 2004) found effects for both, but in the present task these cannot be dissociated since they predict the same behaviour. It is likely however that room landmarks did contribute to the *room* advantage, as previous studies indicate external landmark use at ages even younger than those tested here (e.g. at 22 months; Newcombe et al., 1998). Landmark use is associated with the hippocampus, where damage impairs memory for locations defined by distant visual landmarks in humans (King, Burgess, Hartley, Vargha-Khadem, & O'Keefe, 2002) and rats (Morris, Garrud, Rawlins, & O'Keefe, 1982; Pico, Gerbrandt, Pondel, & Ivy, 1985), and neurons directly reflect memory for locations relative to landmarks in rats (e.g. Lenck-Santini, Muller, Save, & Poucet, 2002; O'Keefe & Speakman, 1987) and humans (Ekstrom et al., 2003).

The final result was children's emerging ability, at 5 years, for viewpoint-independent recall using only the *array* frame of reference. As noted above, viewpoint-independent representations of locations relative to landmarks are associated with the hippocampus, which appears to be able to simultaneously support separate representations referenced to local and to room landmarks (Zinyuk, Kubik, Kaminsky, Fenton, & Bures, 2000). A second component of the ability to use only the *array* frame of reference may be inhibition of the incorrect *body* and *room* frames. Competence on inhibition tasks is considered to depend on the development of the frontal lobes (Diamond, 1990; Goldman-Rakic, 1987).

In conclusion, the *body* frame of reference probably depends on purely egocentric representations such as visual scenes in the ventral stream, while the *room* frame of reference may depend on egocentric representations that are spatially updated by self-motion (dependent on dorsal stream and posterior parietal cortex), as well as allocentric representations of location relative to landmarks within the room (dependent on the hippocampus). Our results suggest that these processes were already present and well developed at 3 years. The later emergence of viewpoint-independent recall using only visual cues within the array implies intrinsic representations of the array, which may depend on further hippocampal and prefrontal development. These suggestions are speculative but can be tested in future studies with clinical groups.

The apparent emergence of viewpoint independence at a later developmental stage in previous related tasks (Huttenlocher & Presson, 1973; Piaget & Inhelder, 1967) may have been partly due to their additional requirement for taking the perspective of another being. Comparing the developmental time course of perspective-taking as opposed to the use of different spatial frames of reference for search may shed light on developmental disorders relating to "theory of mind" (Frith & de Vignemont, in press) or schizotypy (Langdon & Coltheart, 2001). Our current task already has a clear application to the assessment of spatial representations in children with focal brain injury, and in children and adults with developmental disorders. In a range of neurodevelopmental disorders, dorsal stream function shows deficits relative to ventral (Braddick et al., 2003). In our task, (i) *body*-consistency effects, which we have hypothesised depend on ventral stream processing and (ii) *room*-consistency effects, which we have hypothesised depend to a degree on the dorsal

stream, can be dissociated. Groups to which the task would usefully be applied include Down syndrome, a genetic disorder which may include hippocampal dysfunction (Pennington, Moon, Edgin, Stedron, & Nadel, 2003), and Williams Syndrome (Jarrod, Baddeley, & Hewes, 1998), a genetic disorder with spatial and navigational deficits whose neural and cognitive basis is not well understood.

An important result from this study was that children as young as 3 years showed no evidence of the spatial “egocentrism” reported in very early childhood, but were strongly influenced by the hidden object’s place within the environment. The early presence of distinct representations taking into account body and environment, used in parallel across the age range 3–6 years, indicate a continuum with adult performance (Wang & Simons, 1999). The mechanisms that underlie these representations are likely to be shared in young children, adults and potentially other species.

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References

- Acredolo, L. P. (1978). Development of spatial orientation in infancy. *Developmental Psychology*, *14*, 224–234.
- Braddick, O., Atkinson, J., & Wattam-Bell, J. (2003). Normal and anomalous development of visual motion processing: Motion coherence and ‘dorsal-stream vulnerability’. *Neuropsychologia*, *41*, 1769–1784.
- Bremmer, F., Duhamel, J.-R., Ben Hamed, S., & Graf, W. (1997). The representation of movement in near extra-personal space in the macaque ventral parietal area (V.I.P.). In P. Thier, & H. O. Karnath (Eds.), *Parietal lobe contributions to orientation in 3D space*. Heidelberg: Springer.
- Bremner, J. G., & Bryant, P. (1977). Place versus response as the basis of spatial errors made by young infants. *Journal of Experimental Child Psychology*, *23*, 162–171.
- 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.
- Colby, C. L. (1999). Parietal cortex constructs action-orientated spatial representations. In N. Burgess, K. J. Jeffery, & J. O’Keefe (Eds.), *The hippocampal and parietal foundations of spatial cognition*. Oxford: Oxford University Press.
- Diamond, A. (1990). Developmental time course in human infants and infant monkeys, and the neural bases of inhibitory control in reaching. *Annals of the New York Academy of Sciences*, *608*, 637–676.
- Diwadkar, V. A., & McNamara, T. P. (1997). Viewpoint dependence in scene recognition. *Psychological Science*, *8*, 302–307.
- Ekstrom, A. D., Kahana, M. J., Caplan, J. B., Fields, T. A., Isham, E. A., Newman, E. L., et al. (2003). Cellular networks underlying human spatial navigation. *Nature*, *421*, 184–188.
- Epstein, R., Graham, K. S., & Downing, P. E. (2003). Viewpoint-specific scene representations in human parahippocampal cortex. *Neuron*, *37*, 865–876.
- Farrell, M. J., & Robertson, I. H. (1998). Mental rotation and the automatic updating of body-centered spatial relationships. *Journal of Experimental Psychology: Learning Memory and Cognition*, *24*, 227–233.

- Frith, U., & de Vignemont, F. (in press). Egocentrism, allocentrism, and asperger syndrome. *Consciousness and Cognition*. doi:10.1016/j.concog.2005.04.006.
- Goldman-Rakic, P. S. (1987). Development of cortical circuitry and cognitive function. *Child Development*, 58, 601–622.
- Huttenlocher, J., Newcombe, N., & Sandberg, E. (1994). The coding of spatial location in young children. *Cognitive Psychology*, 27, 115–147.
- Huttenlocher, J., & Presson, C. C. (1973). Mental rotation and the perspective problem. *Cognitive Psychology*, 4, 277–299.
- Jarrold, C., Baddeley, A. D., & Hewes, A. K. (1998). Verbal and nonverbal abilities in the Williams syndrome phenotype: Evidence for diverging developmental trajectories. *Journal of Child Psychology and Psychiatry*, 39, 511–523.
- Judd, S. P., & Collett, T. S. (1998). Multiple stored views and landmark guidance in ants. *Nature*, 392, 710–714.
- King, J., Burgess, N., Hartley, T., Vargha-Khadem, F., & O'Keefe, J. (2002). Human hippocampus and viewpoint dependence in spatial memory. *Hippocampus*, 12, 811–820.
- Langdon, R., & Coltheart, M. (2001). Visual perspective-taking and schizotypy: Evidence for a simulation-based account of mentalizing in normal adults. *Cognition*, 82, 1–26.
- Lenck-Santini, P. P., Muller, R. U., Save, E., & Poucet, B. (2002). Relationships between place cell firing fields and navigational decisions by rats. *Journal of Neuroscience*, 22, 9035–9047.
- Levinson, S. C. (2003). *Space in language and cognition: Explorations in cognitive diversity*. Cambridge: Cambridge University Press.
- Loomis, J. M., Klatzky, R. L., Golledge, R. G., Cicinelli, J. G., Pellegrino, J. W., & Fry, P. A. (1993). Nonvisual navigation by blind and sighted: Assessment of path integration ability. *Journal of Experimental Psychology: General*, 122, 73–91.
- McBurney, D., Gaulin, S. J. C., Devineni, T., & Adams, C. (1997). Superior spatial memory of women: Stronger evidence for the gathering hypothesis. *Evolution and Human Behavior*, 18, 165–174.
- Milner, A. D., & Goodale, M. A. (1995). *The visual brain in action*. Oxford: Oxford University Press.
- Mittelstaedt, M. L., & Mittelstaedt, H. (1980). Homing by path integration in a mammal. *Naturwissenschaften*, 67, 566–567.
- Morris, R. G., Garrud, P., Rawlins, J. N., & O'Keefe, J. (1982). Place navigation impaired in rats with hippocampal lesions. *Nature*, 297, 681–683.
- Nadel, L., & Hardt, O. (2004). The spatial brain. *Neuropsychology*, 18, 473–476.
- Newcombe, N., & Huttenlocher, J. (1992). Children's early ability to solve perspective-taking problems. *Developmental Psychology*, 28, 635–643.
- Newcombe, N., Huttenlocher, J., Bullock-Drumme, A., & Wiley, J. G. (1998). The development of spatial location coding: Place learning and dead reckoning in the second and third years. *Cognitive Development*, 13, 185–200.
- O'Keefe, J., & Speakman, A. (1987). Single unit activity in the rat hippocampus during a spatial memory task. *Experimental Brain Research*, 68, 1–27.
- Pennington, B. F., Moon, J., Edgin, J., Stedron, J., & Nadel, L. (2003). The neuropsychology of down syndrome: Evidence for hippocampal dysfunction. *Child Development*, 74, 75–93.
- Piaget, J., & Inhelder, B. (1967). *The child's conception of space*. New York: Norton (first published 1948).
- Pico, R. M., Gerbrandt, L. K., Pondel, M., & Ivy, G. (1985). During stepwise cue deletion, rat place behaviors correlate with place unit responses. *Brain Research*, 330, 369–372.
- Rosetti, Y. (1998). Implicit short-lived motor representations of space in brain damaged and healthy subjects. *Consciousness and Cognition*, 7, 520–558.
- Roskos-Ewoldsen, B., McNamara, T. P., Shelton, A., & Carr, W. (1998). Mental representations of large and small spatial layouts are orientation dependent. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 24, 215–226.
- Simons, D. J., & Wang, R. F. (1998). Perceiving real-world viewpoint changes. *Psychological Science*, 9, 315–320.
- Wang, R. F., & Simons, D. J. (1999). Active and passive scene recognition. *Cognition*, 70, 191–210.
- Zinyuk, L., Kubik, S., Kaminsky, Yu., Fenton, A. A., & Bures, J. (2000). Understanding hippocampal activity by using purposeful behavior: Place navigation induces place cell discharge in both task-relevant and task-irrelevant spatial reference frames. *Proceedings of the National Academy of Sciences USA*, 97, 3771–3776.