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A viewpoint-independent process for spatial reorientation

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ABSTRACT

Reorientation tasks, in which disoriented participants attempt to relocate objects using different visual cues, have previously been understood to depend on representing aspects of the global organisation of the space, for example its major axis for judgements based on geometry. Careful analysis of the visual information available for these tasks shows that successful performance could be based on the much simpler process of storing a visual 'snapshot' at the target location, and subsequently moving in order to match it. We tested 4–8-year olds on a new spatial reorientation task that could not be solved based on information directly contained in any retinal projection that they had been exposed to, but required participants to infer how the space is structured. Only 6–8-year olds showed flexible recall from novel viewpoints. Five-year olds were able to recall locations given movement information or a unique proximal landmark, but without these they could not do so, even when they were not disoriented or when the landmark was a familiar object. These results indicate that early developing spatial abilities based on view matching and self motion are supplemented by a later-developing process that takes into account the structure of spatial layouts and so enables flexible recall from arbitrary viewpoints.

1. Introduction

In development, children show increasingly complex and flexible spatial skills. Elements of visual landmark use emerge at around six months, beginning with use of direct beacons by 6–9 months and followed by the use of indirect markers by 9 months (Acredolo & Evans, 1980; Crowther, Lew, & Whitaker, 2000; Lew, Bremner, & Lefkovitch, 2000). By the end of the first year, infants show rudimentary "path integration" (Schmuckler & Tsang-Tong, 2000) – that is, the ability to track their own movement in order to relocate places in the environment after moving to a new location (Loomis et al., 1993). By 18–24 months toddlers can relocate hidden objects using the surface geometry of enclosed spaces (Hermer & Spelke, 1994, 1996), or using a combination of visual landmarks and path integration (Newcombe, Huttenlocher, Drummey, & Wiley, 1998). By 5 years children can recall locations in a spatial array from a novel viewpoint even when the viewpoint change is not produced by the viewer's own movement – i.e. using landmarks alone, without path integration (Nardini, Burgess, Breckenridge, & Atkinson, 2006). This last result may signal the development of 'viewpoint independence' in spatial memory: the ability to retrieve locations from an arbitrary viewpoint, even one that has not been experienced before.

While spatial cognitive development includes several components, here we focus on the major distinction between *viewpoint-dependent* and *viewpoint-independent* representations of space. Viewpoint-dependent representations are those that adopt a coordinate system centred on a particular viewpoint – a stored view (mental 'snapshot') of a scene is viewpoint-dependent. A viewpoint-

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dependent representation would be of limited use after a change of position. By contrast, viewpoint-independent representations adopt a coordinate system centred on external objects, or on the external environment (Marr & Nishihara, 1978). A 'cognitive map' expressing the relationship between elements of an environment, independent of the viewer, (Gallistel, 1990; O'Keefe and Nadel, 1978) is viewpoint-independent. A viewpoint-independent representation would allow accurate recall from arbitrary viewpoints. Movement-updated representations used in path integration are centred on the viewer, but also allow recall from multiple viewpoints (Loomis et al., 1993). However their accuracy depends on how accurately the viewer can track their own movement, and path integration processes are not properly considered viewpoint-independent.

The thesis that human and animal cognition includes viewpoint-independent representations of space has a long history (e.g. O'Keefe and Nadel, 1978; Tolman, 1948), but remains controversial. For example, Wang and Spelke (2002) have argued that humans navigate primarily by momentary, egocentric representations tied to the body and to particular viewpoints (but see also Burgess, 2006). In this paper we propose that developmental changes in spatial behaviour include a shift from an early reliance on viewpoint-dependent representations, such as remembered visual scenes, to later acquisition of flexible, viewpoint-independent representations of space. To support this thesis, our challenge is to show a spatial behaviour that cannot be explained by a viewpoint-dependent process. This is not straightforward, since in nearly all spatial situations, both viewpoint-dependent and viewpoint-independent explanations can account for behaviour. Consider the simple environment in Fig. 1a, where the task is to relocate the nonvisible target *X* – say, a ball concealed in tall grass. The surrounding landmarks will obviously be useful for relocating *X*; however these landmarks can potentially be used in several different ways, two of which we will contrast here.

First, the viewer might encode the topological structure of the space (Fig. 1b). This depends on inferring three-dimensional metric information from two-dimensional retinal projections, which is a complex but tractable problem. The payoff is that a viewpoint-independent representation of environment structure would provide an excellent basis for relocating *X* (O'Keefe and Nadel, 1978). A second possibility is simply storing a view or 'snapshot' of how the world looks when one is standing at *X* (Fig. 1c). The viewer can then navigate to *X* from a new starting point by moving so as to best match the current view to the 'snapshot' that was stored there. Stored views support navigation in insects (Cartwright & Collett, 1982; Judd & Collett, 1998), and familiar views also facilitate recall in human spatial memory (Diwadkar & McNamara, 1997; Shelton & McNamara, 1997). The key difference between "structural" and "view matching" accounts of the task in Fig. 1a–c is that in the first case the viewer makes spatial inferences beyond what is directly available in the 2D optic array, whereas in the second case the spatial information contained in the 2D projection is considered sufficient.

It has been argued that storing and matching views from specific viewpoints can account for much of both animal and human spatial cognition (Wang & Spelke, 2002). To appreciate the force of this argument, consider (in addition to the imaginary example in Fig. 1a–c) two real spatial tasks. Cheng's (1986) reorientation task (Fig. 1d) has been very widely used to study animal and human navigation and its development (reviewed, Cheng & Newcombe, 2005). Having learnt where an object is hidden, participants are disoriented, so that they cannot keep track of the object's location relative to themselves. A key finding is that both rats (Cheng, 1986) and young children (Hermer

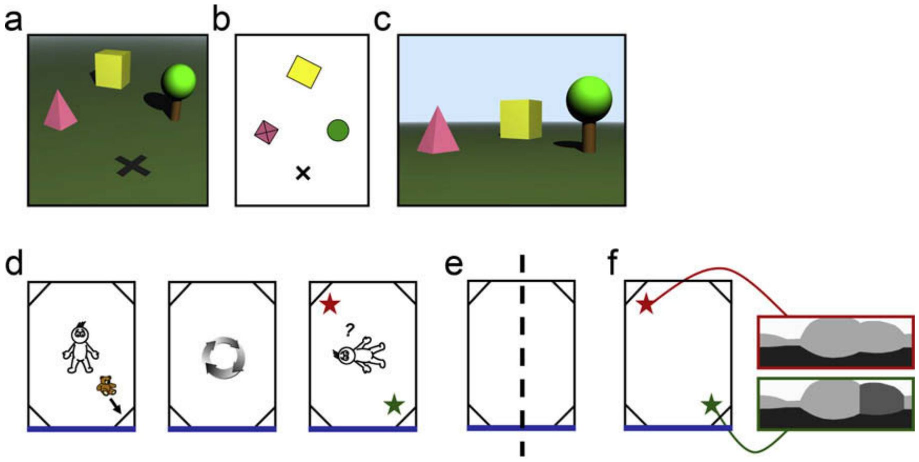

Fig. 1. (a) A simple environment, (b) its topological structure, and (c) the view from *X* (see main text). (d) In the classic reorientation task, participants see an object hidden in one corner of a rectangular enclosure, then search for it after being disoriented by turning. A key developmental finding (Hermer & Spelke, 1994, 1996), paralleling earlier work with rats (Cheng, 1986) is that young children search both "geometrically correct" corners, which are equivalent in terms of geometry (★). They tend to fail to distinguish these further by adjacent wall colour (see also Learmonth et al., 2002). (e) Use of geometry can be explained by coding locations relative to the enclosure's first principal axis, which entails forming a structural representation of the space. (f) Use of geometry can equally be explained by navigating to match the current view with a stored view of how the surroundings look when one is standing at the target corner. Geometric information is strongly manifested in 360° panoramic views (adapted from Stürzl et al., 2008); thus "view-based navigation" can predict reliance on geometry (and the tendency to confuse ★ corners) without any representation of the global structure of the space.

& Spelke, 1994, 1996) are able to relocate objects using the "geometric" cue provided by room shape.

Use of geometry was initially thought to depend on representing locations relative to some aspect of the enclosure's global structure, such as its principal axis (Cheng & Gallistel, 2005; Gallistel, 1990). More recently, Cheng and colleagues observed that view matching is enough to guide solutions based on geometry (Cheng, 2008; Stürzl, Cheung, Cheng, & Zeil, 2008). Results from their simulations are illustrated in Fig. 1f. The view from any place in the enclosure can be described as a 360° panoramic 'snapshot' of the surroundings. To relocate a target corner using view matching, the viewer must store a snapshot of how the surroundings look when one is standing at that corner. On subsequent trials, the viewer relocates the corner by moving in the direction that reduces the discrepancy between the current view and the stored snapshot. This tends to lead to a place where the current view matches the stored view. It turns out that navigation by view matching can account for the successful use of geometry, and also for the relative disregard of non-geometric wall features such as colours and patterns (Stürzl et al., 2008). Importantly, this shows that view matching in the form of simple point-by-point comparison of 2D projections could guide searches based on 'geometry', without viewers having to infer anything at all about the structure of the 3D space. This "view matching" model of the reorientation task raises an interesting question about its development. While young children make errors on the task, using geometry but tending to ignore wall colours (Hermer & Spelke, 1994, 1996; but see also Learmonth, Nadel, & Newcombe, 2002; and review, Cheng & Newcombe, 2005), by 6 years children invariably succeed on all aspects of the task (Hermer-Vazquez, Moffet, & Munkholm, 2001; Learmonth et al., 2002; Learmonth, Newcombe, Sheridan, & Jones, 2008). One account of development would be that view matching improves in accuracy. An alternative possibility is that early view matching is supplemented by a more sophisticated process for solving the task.

A second illustration of how view matching might explain the use of visual landmarks comes from the array rotation task of Nardini et al. (2006). In this study, children saw a toy hidden under one of 12 cups bordered by landmarks, and had to relocate it, sometimes after a change of viewpoint. When a viewpoint change was produced by the array being rotated while the child stayed in the same place, the participant had no movement information about the change. Retrieval therefore could not be supported by path integration, but depended solely on the visual landmarks within the array. In this condition, children aged 5 years (but not 3 or 4 years) successfully relocated the toy. One interpretation of the development seen in this task is that at 5 years, children developed the ability to form a structural description, or 'mental map' of the array. This would enable them to pinpoint locations from arbitrary viewpoints. An alternative explanation is that what developed was the ability to match the configuration of visual features close to the hiding place with a stored view of these features as they appeared when the object was hidden. Although the stored view and test view would no longer match, the features close to the hiding place might still be recognised from the new viewpoint. As with the two accounts of the Cheng task, the first account posits extracting structural information about the space, whereas the second posits relying on relatively unstructured relationships (e.g. 'near to') between cues directly present in the 2D optic array.

In the present study we developed a new test for viewpoint-independent recall in spatial memory – that is, recall even from viewpoints at which visual cues in the scene cannot be matched to those in any stored view. We disoriented subjects (precluding path integration) and used a new search task that precluded viewpoint-dependent solutions such as view matching, or aiming towards any familiar visual feature. To exclude such solutions we devised a situation in which no unique visual cue, available when an object was hidden, could be seen at the time of retrieval. The hidden object therefore could not be relocated using information directly available in the retinal projection of the scene (as the classic reorientation task potentially could; Stürzl et al., 2008). Instead, relocating the object from the novel viewpoint depended on representing the structure of the environment. We tested 4–7-year old children, who are at a transitional age for recall from novel viewpoints without movement information (Nardini et al., 2006).

2. Experiment 1

In a featureless curtained enclosure (W300 × D300 × H230 cm), 4–8-year olds saw a toy hidden in one of two 22 × 22 × 30 cm boxes placed symmetrically either side of a large left-right symmetric landmark with different colourful and geometric features on its front and back (Fig. 2a–b). The landmark comprised a rectangular 60 × 30 × 110 cm box, covered with green fabric on the front and white on the back, joined to a 48 × 26 × 80 cm 'pyramid' (irregular tetrahedron) covered in blue sequinned fabric, symmetric from the front view and vertical (flush with the box) at the back. Each of the two views of the landmark (front/back; Fig. 2a) was seen at hiding on half of trials. Children searched for the toy after being disoriented (moved and turned with eyes closed on an office chair outside the enclosure), and replaced to have either the *same view*, or a *different-view* from the opposite side of the space; see Fig. 2b. Control *no landmark* trials in which the landmark was absent at hiding and retrieval checked that participants had no other cues to location and that the disorientation procedure was effective.

Before starting the series of trials, participants walked around the enclosure to see the landmark from all sides. They then completed 12 trials: four pairs of *same view* and *different view* trials (randomly ordered), followed by four *no landmark* trials. Searching the box gave participants feedback on each trial. When they answered incorrectly, participants were allowed to search the other box. The four trials in each of the same- and different-viewpoint conditions comprised the four possible combinations of initial view relative to the landmark ('front', 'back'), and hiding place relative to the landmark (left, right). We used this small number of trials, with no training, so that subjects could not learn paired associations between different-views of the space. Each *different view* trial was unique, in that the participant had never previously attempted a *different view* test using that combination of initial viewpoint and hiding place. Participants therefore had no previous opportunity to learn the correct answer from the opposite view.

Disorientation prevented participants from tracking their location in the space, and no unique visual cue directly or indirectly indicated the target box. Three potential strategies remained: 1. maintaining a direction relative to the self (“my left”), 2. coding the target’s place in a visual scene (view or ‘snapshot’) stored at hiding, and 3. representing the spatial relations in the room (e.g. between the hiding place, landmark, and different-viewpoints). Strategies 1 and 2 would provide correct solutions to *same view* trials, but incorrect (or no) solutions to *different view* trials (Fig. 2b). Only a representation of environment structure would enable solution of both kinds of trials. *Different view* trials therefore provided a strict test for participants’ ability to represent the structure of the spatial layout.

Participants (recruited from volunteer databases in Oxford and London, and tested with their parents’ informed consent) were 16 4-year olds (mean age = 4.2, s.d. 0.2, range = 4.1–4.7 years), 15 5-year olds (mean age = 5.4, s.d. 0.2, range = 5.1–5.9 years) and 18 6–8-year olds (mean age = 7.4, s.d. 0.5, range = 6.8–8.3 years). After a pilot study found that older children used extraneous cues such as creases in the enclosure fabric to solve *no landmark* trials, the oldest group was tested in a different space (270 × 330 × 230 cm; Fig. 2c) in which these minor visual cues were more carefully controlled and disorientation took place inside the enclosure.

Table 1 shows mean proportions of correct searches by age group and condition. Proportions of correct searches were compared with chance (0.50) using two-tailed one-sample *t*-tests. All groups were significantly above chance on *same view* trials; at 4 years, $M = 0.77$, $t(15) = 3.78$, $p < 0.01$; at 5 years, $M = 0.77$, $t(14) = 4.30$, $p < 0.001$; at 6–8 years, $M = 0.71$, $t(17) = 2.29$, $p < 0.05$. On *different view* trials only 6–8-year olds were significantly above chance, $M = 0.64$, $t(17) = 2.56$, $p < 0.05$; 5-year olds were at chance, $M = 0.47$. $t(14) = 0.52$, $p = 0.61$, while 4-year olds were significantly below chance, $M = 0.33$, $t(15) = 2.42$, $p < 0.05$. No group differed significantly from chance on *no landmark* trials (Table 1); at 4 years, $t(15) = 0.68$, $p = 0.51$, at 5 years, $t(14) = 0.44$, $p = 0.67$, at 6–8 years, $t(17) = 0.24$, $p = 0.82$. This confirms that no group was incompletely disoriented or able to use any extraneous spatial cue.

Table 1
Mean proportion of correct searches (standard error of the mean) by experiment, age group and condition.

	Age, years (n)	Same view condition	Different-view condition	No landmark condition
Exp 1	4 (n = 16)	0.77 (0.07)*	0.33 (0.07)*	0.45 (0.07)
	5 (n = 15)	0.77 (0.06)*	0.47 (0.06)	0.48 (0.04)
	6–8 (n = 18)	0.71 (0.09)*	0.64 (0.05)*	0.51 (0.06)
Exp 2, movement information	5 (n = 8)	0.88 (0.09)*	0.94 (0.06)*	–
Exp 3, distinctive feature	5 (n = 16)	0.75 (0.08)*	0.66 (0.07)*	0.57 (0.08)
Exp 4, landmark rotation	5 (n = 13)	0.65 (0.05)*	0.40 (0.09)	0.50 (0.04)
Exp 5, familiar object	5 (n = 16)	0.80 (0.06)*	0.55 (0.05)	0.55 (0.05)

* Differs significantly from chance (0.50) on two-tailed one-sample *t*-test at the 5% level.

Thus without any unique direct visual cue to the box, but from a familiar viewpoint (condition *same view*), all ages showed reliable recall. Strikingly, when the viewpoint changed (condition *different-view*), below-chance performance showed that children as old as 4 years consistently searched egocentrically, an error that is overcome at nine months when movement information and unique visual cues are available (Bremner, 1978). This bears out the dominance of view- and movement-based representations of space in early childhood (Wang & Spelke, 2002). At

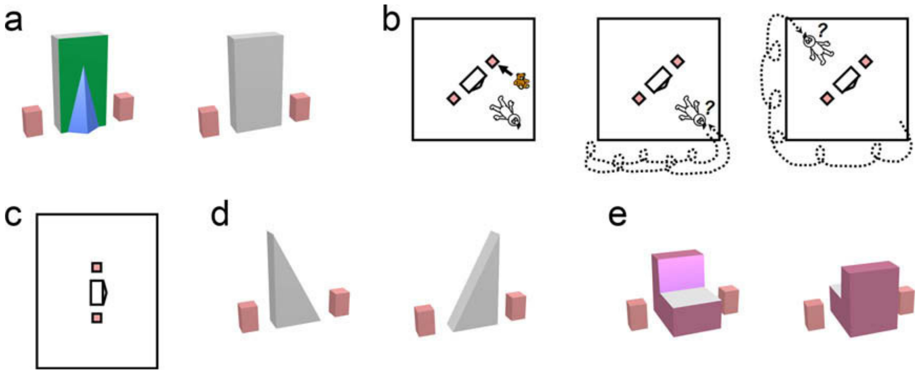

Fig. 2. (a) Landmark and hiding boxes for Experiments 1, 2, and 4, front and back views. (b) General procedure. After seeing the toy hidden on either side of the landmark, participants searched for it after being disoriented and replaced on the same side or on the opposite side. (c) Conditions for Experiment 1, age group 6–8 and Experiment 5 were identical except that the landmark was in a rectangular enclosure and disorientation took place inside. (d) “Wedge”; landmark for Experiment 3; (e) Armchair; landmark for Experiment 5.

5 years *different view* performance was at chance – neither systematically correct nor incorrect – indicating a transitional stage at which children applied different strategies to *same* and *different view* trials, but did not yet consistently solve the latter.

The *different view* condition was eventually solved at 6–8 years. Solution of this task from an unfamiliar viewpoint, without movement information or any unique direct or indirect visual cue, reveals an additional, later-developing viewpoint-independent process for spatial reorientation. At 6–8 years this process was selected in favour of competing egocentric processes, which signalled the wrong location. The ability of 6–8-year olds to solve the task shows that children at this age had not only viewpoint-dependent representations (such as "my left" or a viewpoint-specific "snapshot"), but also structural information about spatial relations within the enclosure.

3. Experiment 2

Chance performance in Experiment 1 indicates that 5-year olds are transitional for solving the different-view test. In Experiments 2–5 we manipulated the available spatial information to investigate the abilities of this age group further. In Experiment 2, we checked that 5-year olds ($n = 8$; mean age = 5.3, s.d. = 0.22, range = 5.1–5.8 years) could solve the *different view* test when movement information accompanied the perspective change. A smaller group was recruited as we expected a strongly positive result by 5 years based on previous studies (e.g. Newcombe et al., 1998). The procedure followed that for Experiment 1, except that instead of being placed on an office chair and disoriented, children slowly wheeled the chair outside the enclosure and back to the same view or to the opposite view. Participants had their eyes open, but could not see inside the enclosure while they were outside. Performance (Table 1) was significantly above chance for both *same view*, $M = 0.88$, $t(7) = 3.97$, $p < 0.01$, and *different-view* trials, $M = 0.94$, $t(7) = 7.00$, $p < 0.001$. This confirms that when movement information is available, 5-year olds very easily relocate the toy from the opposite viewpoint. Movement information allows the continual updating of the target box's position relative to the participant by path integration (Loomis et al., 1993). Walking to the new viewpoint also informs participants that their perspective has changed, which may help to suppress the incorrect viewpoint-dependent response.

4. Experiment 3

In Experiment 3 we tested whether 5-year olds ($n = 16$, mean age = 5.4, s.d. = 0.2, range = 5.1–5.8 years) could solve the *different view* test without movement information, but with a local cue that is visible from both viewpoints. The setup and procedure were identical to Experiment 1, except that the central landmark was wedge-shaped (60 × 30 × 110 cm; Fig. 2d), i.e. with distinctive geometric features that can be seen from both sides. Performance (Table 1) was significantly above chance both on *same view*, $M = 0.75$, $t(14) = 2.96$, $p < 0.01$, and on *different-view* trials, $M = 0.66$, $t(14) = 2.25$, $p < 0.05$. The control *no landmark* condition did not differ from chance, $M = 0.57$, $t(14) = 0.89$, $p = 0.39$. This result shows that in the absence of movement information, an indirect visual cue sufficed to allow 5-year olds to relocate the toy from the opposite viewpoint. This is consistent with 5-year olds' solution of a similar problem in a small spatial array (Nardini et al., 2006). As well as providing a unique visual feature near the hiding place, the large difference between front and back views of this landmark may help to signal a change of viewpoint, which could suppress the incorrect viewpoint-dependent response.

5. Experiment 4

While disorientation by turning is commonly used to eliminate internal directional cues, the disoriented state is unusual, and may disrupt neural mechanisms of spatial learning (Knierim, Kudrimoti, & McNaughton, 1995). We tested whether 5-year olds' failure to find a viewpoint-independent solution to Experiment 1 was specific to the disoriented state. The Experiment 1 landmark and boxes (Fig. 2a) were fixed to a trolley, and after seeing the toy hidden as before, participants ($n = 13$, mean age = 5.5, s.d. = 0.3, range = 5.0–5.9 years) stood outside the enclosure while the experimenter moved and rotated the trolley, either to the same orientation as at hiding, or to the opposite orientation. The trolley was also moved to be adjacent to one of the enclosure walls, to highlight that a change might have occurred. Before starting, the experimenter demonstrated that the trolley, landmark and boxes all moved together. Performance (Table 1) was above chance on *same view*, $M = 0.65$, $t(12) = 2.89$, $p < 0.02$, but not different from chance on *different view*, $M = 0.40$, $t(12) = 1.10$, $p = 0.29$ or *no landmark* trials, $M = 0.50$, $t(12) = 0.00$, $p = 1.00$. Thus even when they were not disoriented, 5-year olds failed to show viewpoint-independent recall.

6. Experiment 5

Spatial studies commonly require participants to learn new landmarks and environments, and may thus underestimate their abilities with landmarks for which they have formed more established schemata. In Experiment 5 we re-ran the basic task (Experiment 1) using a 59 × 73 × 78 cm burgundy armchair, covered in white fabric (on the seat) and purple sequinned fabric (on the back-rest), as the landmark. This more familiar object was structurally equivalent to the original landmark in being symmetric and having different geometric and colour features on its front and back (Fig. 2e). Before starting the study, children sat in the armchair to reinforce their understanding of it as a familiar object. Participants ($n = 16$, mean age = 5.4, s.d. = 0.3, range = 5.0–5.9 years) followed the Experiment 1 procedure, using the larger enclosure (Fig. 2c). Mean scores (Table 1) were significantly above chance on *same view*, $M = 0.80$, $t(15) = 5.22$, $p < 0.001$, but not on *different-view*, $M = 0.55$, $t(15) = 1.00$, $p = 0.33$ or *no landmark* trials, $M = 0.55$, $t(15) = 0.90$,

$p = 0.38$. Thus 5-year olds also failed to show viewpoint-independent recall relative to a familiar object whose layout could have been acquired over time.

7. General discussion

We tested the hypothesis that development of flexible spatial behaviour in childhood includes the emergence of a viewpoint-independent process, supplementing earlier-developing processes based on familiar views and movement-based updating (path integration). To test specifically for viewpoint-independent recall, the *different view* condition was designed so that it could only be solved if participants understood the structural relationship between the landmark and target.

When the toy was both hidden and retrieved from the *same* viewpoint, children's recall was reliable over all ages and experimental manipulations. Success on this condition is consistent with use of viewpoint-dependent representations based on encoding a direction relative to the self ("my left"), or encoding the target's place within a visual scene. It is also, in principle, consistent with viewpoint-independent recall.

Retrieval from the *different* viewpoint provided a strict test for viewpoint independence. On this condition, 4-year olds were significantly below chance, i.e. consistently incorrect. This suggests that they used the same, viewpoint-dependent strategy on both *same view* and *different-view* trials. They may just have encoded a direction relative to themselves, and/or encoded the visual scene in an elementary way that did not capture visual differences between the front and back views of the landmark object.

Five-year olds' *different view* performance was at chance, which suggests that they used different strategies for same- and different-view trials, but did not find a consistent viewpoint-independent solution. This is consistent with participants recognising that the changed view calls for a different response, but responding randomly, and also with participants using a mixture of correct and incorrect approaches to solving the task. Thus, the 5-year old group showed the ability to recognise when the view has changed, but did not translate this consistently into a successful strategy for retrieving the toy. Five-year olds were unable to retrieve the toy from the opposite viewpoint (Experiment 1), unless movement information about their displacement (Experiment 2) or indirect visual cues (Experiment 3) were available. Thus the different-viewpoint test was solved by 5-year olds only when movement-based or viewpoint-dependent solutions were provided. With only viewpoint-independent solutions available, 5-year olds were unable to solve the task, and remained unable to do so even when they were not disoriented (Experiment 4), and when the landmark was a familiar object (Experiment 5).

Five-year olds in the present study seemed to rely on a combination of viewpoint-dependent strategies, that do not go beyond the spatial information directly contained in the optic array, and path integration. This is interesting since by 5 years, children's spatial competencies are relatively advanced: 5-year olds typically solve the classic reorientation task (Hermer-Vazquez et al., 2001; Learmonth et al., 2008), and can use nearby landmarks to relocate hidden objects from novel viewpoints even when no movement information accompanies the viewpoint change (Nardini et al., 2006). The present results suggest that these abilities could be supported by effective view matching. These results also suggest that the abilities of 18–24 month olds to distinguish enclosure corners between blue and white walls (Nardini, Atkinson, & Burgess, 2008) or walls with small and large dots (Huttenlocher & Lourenco, 2007) based on their left/right sense are very likely to be based on view matching rather than on encoding environment structure.

At 6–8 years, children succeeded on the different-view condition (Experiment 1), which implies a flexible, viewpoint-independent process for spatial recall. At this age, a viewpoint-independent process was reliably selected in preference to competing viewpoint-dependent processes. This result indicates that mature human spatial cognition includes viewpoint-independent representations of environment structure (Burgess, 2006), but that these structural representations are developmentally late to emerge or to be selected for action.

The different-view condition depends not only on possessing a viewpoint-independent solution, but also on selecting it in favour of competing egocentric solutions that signal the wrong location which, here, is a visually identical box. As in other tasks in which subjects can choose between responding 'egocentrically' and 'allocentrically' (e.g. Acredolo, 1978; Nardini et al., 2006), suppressing the incorrect egocentric response is a component of the task, likely to depend on the development of inhibitory control (Diamond, 1990). Thus while we can trace the selection of the correct, viewpoint-independent *response* to 6–8 years on the current task, we cannot determine the earliest age at which a viewpoint-independent representation was available. Our key finding is that at least by 6–8 years, children showed a spatial competence that cannot be explained by view-based navigation based on the computationally simple process of matching visual snapshots (Stürzl et al., 2008). However, the earliest age for acquisition of the viewpoint-independent representations supporting this ability remains a question for future research. Newcombe and Huttenlocher (2006) have proposed that developmental changes in spatial behaviour depend on the reweighting of different spatial information sources. In the present study, children's selection of the correct, viewpoint-independent solution (and rejection of the incorrect solution) at 6–8 years could correspond to a reweighting of this kind.

We can rule out simple matching of visual snapshots (Stürzl et al., 2008) as the basis for retrieval, and so conclude that children solved the *different-view* condition by going beyond the information directly present in the optic array to infer something about the environment's structure. Clearly it is important to know more about what aspects of structure were represented, and how. A key question is whether the representations comprise 'survey knowledge' of the space, like a mental map, or are more limited in scope but allow mental operations through which participants can reimagine themselves at the other viewpoint. These processes are conceptually quite different, but it can be difficult to distinguish between them in practice, and the present data are not able to do so. However, both imply that information is available about the structure of the environment. Solving the task by reimagining oneself at the opposite viewpoint requires knowing at least the spatial relationships between the two viewpoints and the target. Imagining displacements around the room requires the use of a coordinate system centred on the room – manipulating or rotating retinal images using only the retinal coordinate system could not solve the *different view* condition. Therefore whether subjects represented the whole space allocentrically, or just represented pairs of spatial relationships (current place to original place, and original place to target), in either case they represented the relevant aspects of how the space is structured that would be needed for flexible recall from the new viewpoint.

One approach to examining underlying spatial representations would be to ask whether response accuracy and latency are the same across different perspectives: additional latency or reduced accuracy from some viewpoints might suggest an additional process such as mental rotation. Studies of latency and accuracy of spatial judgments from different-viewpoints have revealed aspects of how adults code environment structure (Shelton & McNamara, 1997). However, coding with respect to an "intrinsic" reference frame provided by the axis along which objects are organised can also result in a degree of viewpoint-dependence (better recall along this externally defined axis; Mou & McNamara, 2002) – so the use of allocentric coding does not always imply equal performance from all viewpoints. In the present study we would not predict that retrieval should be equally fast or accurate from both viewpoints, as the familiar viewpoint can be solved not only by a viewpoint-independent process (which might, in principle, show equal availability from all viewpoints), but also by a potentially easier viewpoint-dependent processes such as remembering "my left". A detailed comparison of latency and accuracy profiles across a range of viewpoints could be informative in a study designed to exclude parallel availability of simple egocentric strategies. However, the interpretation of such profiles would depend on specific assumptions about the nature of the representation and processes which operate upon it.

A requirement that may have made the task relatively difficult is the need to attend to a central landmark, which may be difficult to use for spatial coding (Collett, Cartwright, & Smith, 1986) compared with distal landmarks (Morris, 1981) or boundary shape (Cheng, 1986). A central landmark and a visually identical foil were necessary to properly control which visual features could be seen from which view, but in principle it might be possible to devise an equivalent test using distal landmarks or boundaries. Lourenco, Huttenlocher, and Vasilyeva (2005) studied whether toddlers could relocate corners first seen inside an enclosure from the outside and vice versa. The ability to understand that a corner seen from inside is the same as one seen outside could provide a strict test for participants' representation of the structure of the space. While 18–26 month olds failed on the original task (unless they remained oriented while the translation from inside to outside took place, enabling them to track their movement), it would be interesting to test older ages on a similar task. In Lourenco and colleagues' study the walls of the enclosure were low enough for participants to see over the top, which means that participants' visual recognition of corners from the outside based on their inside features could not be ruled out. With tall walls precluding viewing of the inside from the outside, a task of this kind could exclude solutions based on view matching.

Our results differ from those in a 'perspective-taking' task (Newcombe & Huttenlocher, 1992), which evaluated children's understanding of different-viewpoints by asking them which object on a table-top would occupy some position relative to themselves (e.g., 'furthest') if they moved to a different-viewpoint. Children as young as 3–4 years named the correct objects. The perspective-taking task may have been easier because it took place in a natural room full of distal landmarks, there was no need to resolve their own orientation, and the instruction to suppress a particular perspective and adopt another was given explicitly. In addition, in perspective change tasks participants know the amount of translation and rotation required, and so can imagine gradually moving to the new viewpoint, spatially updating objects' positions as they do so (Farrell & Robertson, 1998; Rieser, 1989). In a recent study with adults (Valiquette & McNamara, 2007), patterns of viewpoint-independence depended both on whether the location to be remembered was a navigational goal or not, and on the type of test (judgments of relative direction vs. scene recognition). How factors such as these influence the emergence of viewpoint independence in childhood are important questions for further study.

In summary, we found that 6–8-year olds could reorient in a viewpoint-independent manner, whereas 4- and 5-year olds were dependent on viewpoint-dependent representations or those updated with movement. Overall, these results support the thesis that viewpoint-dependent representations form the core of human spatial cognition (Wang & Spelke, 2002), but also show the emergence of a more flexible, viewpoint-independent process. Consistent with its greater computational demands, this process takes much longer to develop or to be selected for action. Future studies should examine in detail how effectively viewpoint-independent and viewpoint-dependent representations combine when both are available. It is likely that humans flexibly integrate different representations depending on the demands of the current task and the reliability of different, potentially competing, cues (Burgess, 2006; Newcombe & Huttenlocher, 2006). How these cues are combined is a problem that Bayesian models of spatial cue integration (Cheng, Shettleworth, Huttenlocher, & Rieser, 2007; Nardini, Jones, Bedford, & Braddick, 2008) may be able to address.

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