Effects of two-dimensional versus three-dimensional landmark geometry and layout on young children's recall of locations from new viewpoints

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ABSTRACT

Spatial memory is an important aspect of adaptive behavior and experience, providing both content and context to the perceptions and memories that we form in everyday life. Young children's abilities in this realm shift from mainly egocentric (self-based) to include allocentric (world-based) codings at around 4 years of age. However, information about the cognitive mechanisms underlying acquisition of these new abilities is still lacking. We examined allocentric spatial recall in 4.5- to 8.5-year-olds, looking for continuity with navigation as previously studied in 2- to 4-year-olds and other species. We specifically predicted an advantage for three-dimensional landmarks over two-dimensional ones and for recalling targets "in the middle" versus elsewhere. However, we did not find compelling evidence for either of these effects, and indeed some analyses even support the opposite of each of these conclusions. There were also no significant interactions with age. These findings highlight the incompleteness of our overall theories of the development of spatial cognition in general and allocentric spatial recall in particular. They also suggest that allocentric spatial recall involves processes that have separate behavioral characteristics from other cognitive systems involved in navigation earlier in life and in other species.

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Introduction

Spatial memory is the metaphorical hook on which our everyday experiences hang; when having a complex interaction with another person, adapting to a new structure of potential rewards, or even having a simple percept of a new sight, sound, or smell, our perceptions come attached to locations that help us to contextualize and organize our experiences. Remembering locations reliably is also crucial for many everyday tasks on both small scales (e.g., finding keys on a cluttered desk) and large scales (e.g., giving directions to a friend). Schemes for remembering spatial locations can be parsed into *allocentric,* meaning world-based and relative to reference points that stay in the same place as the organism moves, and *egocentric,* meaning self-based and relative to the organism (Piaget & Inhelder, 1956). Allocentric memories are generally more useful because they remain stable even after an organism becomes disoriented or leaves an environment and returns later, although the two work together in many situations (e.g., Burgess, 2006). Allocentric spatial cognition is widely found to be more difficult (e.g., Burgess, Spiers, & Paleologou, 2004; King, Burgess, Hartley, Vargha-Khadem, & O'Keefe, 2002; Shelton & McNamara, 2001), to develop later in life (e.g., Acredolo, 1978; Negen, Heywood-Everett, Roome, & Nardini, 2017; Newcombe, Huttenlocher, Drummey, & Wiley, 1998; Piaget & Inhelder, 1956), and to depend on distinct neural substrates (see Bird & Burgess, 2008, for a review). Our recent studies using novel cognitive modeling analyses (Negen & Nardini, 2015; see also Nardini, Burgess, Breckenridge, & Atkinson, 2006) and virtual reality methods (Negen et al., 2017) have shown that allocentric spatial recall emerges shortly after a child's fourth birthday. In this article, our main goal was to better characterize those new allocentric spatial memory skills during middle childhood, specifically 4.5–8.5 years of age.

After reviewing effects seen in other spatial cognition tasks, we chose to focus on two potential factors that we expected to moderate performance: (a) an advantage for three-dimensional (3D) landmarks, where objects in the environment with some appreciable height might allow greater precision of allocentric recall than two-dimensional (2D) markings on the ground (e.g., Lee & Spelke, 2008), and (b) an advantage for targets "in the middle" of a landmark array, allowing greater precision for those targets versus ones that lay elsewhere (e.g., Ankowski, Thom, Sandhofer, & Blaisdell, 2012; Nardini, Thomas, Knowland, Braddick, & Atkinson, 2009). Because so little is known about what factors moderate performance in allocentric spatial memory in this age range, testing these two effects serves to address a major gap in the existing literature.

In the rest of this article, we use navigation as a point of comparison for our allocentric spatial recall task here. The difference in practice is just one of response modality; recall is defined as pointing to a remembered location, whereas navigation is defined as moving to a remembered location. Navigation tasks are much more common in the literature (e.g., Hermer & Spelke, 1994). However, recall tasks provide a stricter measure of children's allocentric reasoning, removing any egocentric methods of succeeding at the task (see Negen et al., 2017; cf. Stürzl, Cheung, Cheng, & Zeil, 2008). Using a recall task allows us to further characterize the cognition that it elicits for comparison with navigation. We hypothesized that two major performance effects in previous navigation studies would also be present in our spatial recall task because both are directed by the goals of understanding and working with spatial information. Alternatively, effects on performance might be very dissimilar because the act of navigating always gives an opportunity to gather and use egocentric information as the organism moves around (e.g., Stürzl et al., 2008), and a spatial recall task might be more related to scene perception or mental rotation skills. Supporting this, the ability to navigate to remembered locations after being disoriented emerges much earlier, from 1.5 to 2.0 years of age (Hermer & Spelke, 1994), versus 4 years of age for a task like ours (Negen et al., 2017). By using virtual reality to force participants to make responses without the aid of any egocentric information, we are both (a) characterizing allocentric spatial recall in greater detail and (b) seeing how similar the use of allocentric information by itself is to the various processes that support navigation, not just in terms of when they emerge but also in terms of what determines performance.

2D and 3D landmarks

Studies regarding navigation suggest a strong advantage for 3D objects over 2D objects both in behavioral performance during early childhood and in neural coding. These findings have been part of a wider line of theory development that clarifies the importance of boundaries (which must be 3D, at least in the sense that this term is generally used) in guiding navigation across a wide variety of species, tasks, short-term timeframes of reconciling incoherent spatial perceptions, and relatively long-term stages of early development (e.g., Gallistel, 2017; Lee, 2017; Xu, Regier, & Newcombe, 2017).

Of particular interest here, there is strong evidence that 3D landmarks are privileged in an early developing form of human navigation—reorientation. In the basic paradigm, adapted from work with rodents (Cheng, 1986), children between 2 and 4 years of age are put in a rectangular enclosure and watch a toy being hidden in one of the corners (Hermer & Spelke, 1994). They are then gently disoriented by turning with their eyes closed and allowed to search for the toy. Several studies have seen children of the same age succeed when the enclosure is a 3D rectangle of walls and fail when it is a 2D marking on the ground (Lee & Spelke, 2008, 2010, 2011). This behavior still stands even when visual features in the 2D/3D cases are very similar (Lee & Spelke, 2010) or the 3D case is visually subtle compared with the 2D case (Lee & Spelke, 2011). The one caveat is that the 3D items need to still have some extended length along the ground; tall thin columns do not allow reorientation to happen at the same age as walls that are longer but shorter in height (e.g., Lee & Spelke, 2008). This suggests that a navigation-relevant cognitive system already exists at 2 to 4 years of age with little or no sensitivity to 2D objects, which could provide an advantage for 3D landmarks in an allocentric spatial recall task later in life if navigation and allocentric spatial recall are strongly continuous.

In addition, neuroscience studies suggest that navigation relies heavily on specialized *boundary vector cells* (e.g., Lever, Burton, Jeewajee, O'Keefe, & Burgess, 2009) and that not all of these cells are not sensitive to the presence of 2D landmarks. These interface with *grid cells* and *place cells* (e.g., Moser, Kropff, & Moser, 2008) to form an integrated system supporting navigation. Recent work suggests that almost all boundary vector cells are sensitive to the presence of 3D objects, but relatively few respond to 2D ones (S. Poulter, S. A. Lee, & C. Lever, personal communication, January 2018; Poulter, Lee, & Lever, in preparation) In addition, 3D geometry is primary in recovering hippocampal representations after disorientation (Keinath, Julian, Epstein, & Muzzio, 2017). Despite potential issues with using rodents to understand the neural underpinning of navigation in humans, neuroimaging studies with adult humans have begun to provide evidence for comparable organization (e.g., Doeller, Barry, & Burgess, 2012; Ekstrom et al., 2003).

All of these results showing a 3D advantage come from navigation tasks or from freely behaving mammals that are exploring a space. Because these paradigms always allow egocentric information to be gathered and applied through the act of movement, it is not clear whether they will apply to a task that forces allocentric information alone to be used. One of our aims that motivated a study of allocentric spatial recall is to see whether the results suggest differences between the cognition underlying navigation and recall. This is done by seeing whether the 3D advantage is also present in a task like the one described here.

In the middle

Performance at navigating to targets in the middle may arise earlier and be easier than more flexible kinds of navigation. Evidence for this claim comes from a widespread theoretical interest in the development and use of multiple landmarks to create a coordinated and durable spatial memory, rather than relying on singular beacons that may more easily shift or be misremembered, in both humans (e.g., Piaget & Inhelder, 1956; Uttal, Sandstrom, & Newcombe, 2006) and other animals (e.g., Collett, Cartwright, & Smith, 1986). This has led to many studies that involve the presentation of a target in relation to an array, followed by the deformation of that array in a way that preserves specific ways of encoding the target but damages others, in order to investigate what systems of relations are encoded and when.

Unfortunately, studies that directly compare targets in the middle versus elsewhere in the exact same circumstances are lacking, but comparing results across studies is still illuminating. Ankowski

et al. (2012) found that 2-year-olds frequently search by nearby landmarks around the space when a target is in the middle, but at 3 years of age most searches were closer to the midpoint than any of the four landmarks. As part of the developmental time course, from 3 to 5 years of age children will readily generalize learning about the middle of one simple geometric environment to a variety of other simple geometric environments (Tommasi & Giuliano, 2014). Children aged 4 or 5 years also seem able to navigate to the middle of two landmarks despite the landmarks being moved farther apart (Uttal et al., 2006). Overall, this suggests that between 2 and 5 years of age, children are acquiring some reliable skill at navigating to remembered targets in the middle.

In contrast, children aged 4 or 5 years show poorer performance at navigating to places that are marked out by other relations to landmarks. Children of this age failed to consistently navigate to a target hidden at either of two sides of a landmark with a distinctive face (Nardini et al., 2009), even performing significantly *below* chance in one condition at 4 years. Children under 5 years also show lower performance at an uncued radial arm maze (Overman, Pate, Moore, & Peuster, 1996), especially in terms of the last four searches, when compared with children over 5 years. Children at 4 years could remember a target in a distinctive container with very high accuracy but failed to distinguish two identical containers when the single distinctive container and two identical containers were in a stable regular triangle (Lee, Shusterman, & Spelke, 2006), forcing them to remember left/right information instead of just being in the middle. The overall pattern is that children under 5 years are able to navigate to targets in the middle of several identical landmarks but have much greater difficulty in navigating to targets with other spatial relations to landmarks such as left versus right.

Further nuancing the possible effects of targets in the middle is the distinction between memory precision and memory bias. A long line of studies have found a *category adjustment effect* or *prototype effect,* where responses are biased toward prototypical placements in some kind of space, with the middle being the most common and most early developing prototype (e.g., Holden, Curby, Newcombe, & Shipley, 2010; Huttenlocher, Hedges, & Duncan, 1991; Huttenlocher, Newcombe, & Sandberg, 1994). The usual explanation is that the prototype serves as the continuous stand-in for a categorical form of memory. For example, if you just remember that a glass was "on the table," that does not specify where on the table, so you begin looking for the glass in the continuous space by letting the center of the table stand in as the best example of being on the table. If both the categorical information and some additional metric information are available, the two are combined by Bayesian (or Bayesian-like) inference and the result is a small but consistent bias toward the middle. Based on this kind of theory, we could expect to see some bias to respond in the middle for a spatial recall task even if the continuous component of memory is not more accurate there. Our analyses will need to account for this distinction.

In terms of language development, it is of interest that the phrase "in the middle" arises much earlier than many other parts of spatial language, which might also suggest that in the middle is a particularly easy spatial relation with which to work. Ankowski et al. (2012) provided a clear demonstration of early language comprehension in a study that used an expansion paradigm in navigation. Children were trained to navigate over to a location that was marked by four posts that were close together. They were then shown the same four posts spread apart. Two-year-olds who were explicitly told that the target was being hidden in the middle navigated over to the middle of the expanded post array. In contrast, none of them navigated to the middle in an uncued control condition. In addition, children failed a test of "left" versus "right" until 6 years of age (Cox & Richardson, 1985) and performed poorly on "in front" and "behind" until then as well. The fact that this piece of language develops so early could reflect an early fluency with the concept of "in the middle" as children navigate.

Because we hypothesized that navigation and allocentric spatial recall would show strong continuity, we expected to see a similar advantage for targets in the middle in our allocentric recall task here. This again means that we were both characterizing recall better and allowing a comparison between recall and navigation.

The current study

Our task was an immersive virtual reality task modified from a recently validated test for the development of allocentric spatial recall (Negen et al., 2017). Children are shown a target in immersive virtual reality and are then "teleported" gently to a new position in the environment. Following this, participants are asked to point to where they thought the target was in the environment. Children under 4 years of age were able to successfully point toward the target when they were either teleported to the encoding viewpoint, allowing egocentric view matching[1] (e.g., Stürzl et al., 2008), or allowed to walk to a new viewpoint, allowing egocentric self-motion strategies (e.g., Newcombe et al., 1998), but not when teleported to a new viewpoint, which defeats both and requires allocentric spatial recall. Children over 4 years achieved success at all conditions. This result, a classic egocentric-to-allocentric shift, validates the method by establishing that it is able to capture well-known and robust effects in terms of spatial cognition.

We modified that method here to ask further questions about allocentric spatial recall. Specifically, we removed the test trials that allowed any egocentric strategy (i.e., a matching viewpoint or the presence of helpful self-motion information) and focused all of our available testing time on trials where participants were teleported to a new viewpoint. We also changed the landmarks and the walkway to objects that allowed a simpler 2D versus 3D manipulation—specifically, a flat checked mat versus a checked box. We also changed the selection of targets to include one that was exactly in the middle of the center points of the two landmarks and others that were counterbalanced around the environment (rather than random targets in an area). Otherwise, the procedure remained very similar. In brief, the task involved the participant watching a small animated character (a mouse) dig underground, but the participant was then teleported to a new viewpoint and needed to point at the character's location by referencing a pair of either 2D (flat) or 3D (raised) symmetric landmarks. Based on previous work (Negen & Nardini, 2015; Negen et al., 2017), we tested children aged 4.5–8.5 years and expected allocentric recall from even the youngest children. These changes allowed us to move over from looking for an egocentric-to-allocentric shift in younger participants toward examining effects that moderate performance with an allocentric frame in participants who had already developed that skill.

Based on a hypothesis of continuity with navigation effects seen in children aged 2–4 years and in other mammals such as mice, we expected two factors to further moderate performance. First, precision will be higher when there are 3D visual landmarks versus similar 2D landmarks. Second, there will be an advantage for remembering locations that are in the middle of two landmarks. We also expected an effect of age (older participants being more accurate) and rotation (shorter teleports leading to more accuracy), which we analyzed to check the basic validity of the task.

Method

Participants

Participants were 15 children aged 4.5–5.5 years, 16 children aged 5.5–6.5 years, and 17 children aged 6.5–8.5 years. All participants were recruited in and around the Durham area of the United Kingdom with full consent from their parents or guardians. Children were eligible for inclusion if their parents reported no developmental concerns or disorders. Demographics were not collected. There was no paid incentive, although children were offered a small reward at the end of the study. The study had approval from the local ethics committee.

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[1] Another strategy that might seem even simpler could also help to a small extent. Participants could practice putting their body in a specific position to point to the target when it was visible and then try to return their body to that position on recall. This could be done even with their eyes closed at the recall time point. Because participants walked in between encoding and recall, they could not be guaranteed to have their body oriented in the same direction as encoding, so the use would be limited, but it could potentially be an additional method to reinforce the memory in these trials that allow egocentric strategies. This method is also defeated by needing to teleport to a new viewpoint.

The youngest age range chosen was taken from children's competency at allocentric spatial recall from 4 years of age (Negen et al., 2017). Therefore, we expected the same type of recall to be evident at some level for children aged 4.5 years. The breakdown of age groups was based on the belief that developmental changes in spatial precision would start to slow markedly at around 7 years of age (e.g., Piaget & Inhelder, 1956). Thus, we expected the 2 years of development between 6.5 and 8.5 years to look more similar at that point. Finally, the chosen sample size of at least 15 participants, with a full dataset, in each age group was based on the reliable success of navigation studies finding 2D versus 3D effects with similar participant numbers (e.g., Lee & Spelke, 2011) but vastly fewer trials.

Apparatus

This experiment was made possible by the use of 16 motion tracking cameras (Vicon Bonita, Vicon, Oxford, UK), which can track the movement of infrared markers with millimeter accuracy at up to 240 Hz when calibrated. This allowed us to track the precise positions of a head-mounted display (Oculus Rift, Oculus, Menlo Park, CA, USA), along with a response (pointing) device and a real 3D box, in real time for a highly responsive and high-frame-rate (90 Hz) rendering.

The two landmarks provided in the environment were red and yellow checked rectangular shapes that were either 2D (30 cm width × 120 cm length) or 3D (same width × same length × 30 cm height) depending on the condition. In the 3D condition, the red landmark was present in both the actual and virtual environments. This allowed participants to stand on the landmark and so experience it as a real object both inside and outside of the virtual reality (see below). Each landmark had two axes of symmetry, and there was an orienting skybox present (see Fig. 1). Because of the symmetry of the landmarks and the infinite-distance rendering of the skybox, target locations could be identified precisely only by using at least two of these cues, which should encourage children to examine their relation and help to bring out (a) relational language such as "in the middle" and (b) encoding relative to geometry, which is a major theoretical aspect of reorientation behavior (e.g., Lee & Spelke, 2011).

The environment had two landmarks set at right angles. Two landmarks were used, as by Uttal et al. (2006), rather than four landmarks (e.g., Ankowski et al., 2012) to make it less ambiguous which point was in the middle. With just two landmarks, there was a single target (D) that was directly between the center points of the landmarks and had the lowest possible average distance to them. If we had used four landmarks, there would actually have been four more points that were in the middle of pairs of landmarks. This way, there was a single point that was objectively in the middle to compare with all other targets. (We return later to a discussion of which targets may feel subjectively "in the middle" as well.) We then placed the landmarks at right angles so that we could arrange for a target (H) that was equidistant from the centers of the two landmarks and also had a sense of alignment with the landmarks (being on the minor axes of both), but not on the line between their centers or directly on any line connecting any of their points, to see whether that had similar effects on precision.

There was a red disc on the floor for participants to stand on, referred to by the experimenter as their "teleporter." The experimenter narrating the experiment and giving instructions was represented virtually by a floating red ball with wings that was tracked to a hat that he was wearing. There was also a light checkerboard shading on the ground to help give a sense of optic flow and distance when moving and viewing the surface. Participants had a small "magic wand" made from a screwdriver handle and some PVC (polyvinyl chloride) cylinders that they used to point to signal their responses. When responding, a small red laser projected from the virtual wand to the floor, where a small inverted white cone pointing at the floor made it as clear as possible where participants were actually responding.

Trial parameters and randomization

There were a total of 10 possible target locations (Fig. 1). The critical in-the-middle target, D, which was directly at the center point of a line connecting the centers of the two landmarks, had 4 trials per block. Another two targets were placed at reflections over each of the landmarks' centers, C and J, also with a total of 4 trials per block (2 each). Similarly, a target that was at the intersection of the two minor axes, H, had 4 trials, and its two reflections, A and G, had 4 trials as well (2 each). An additional
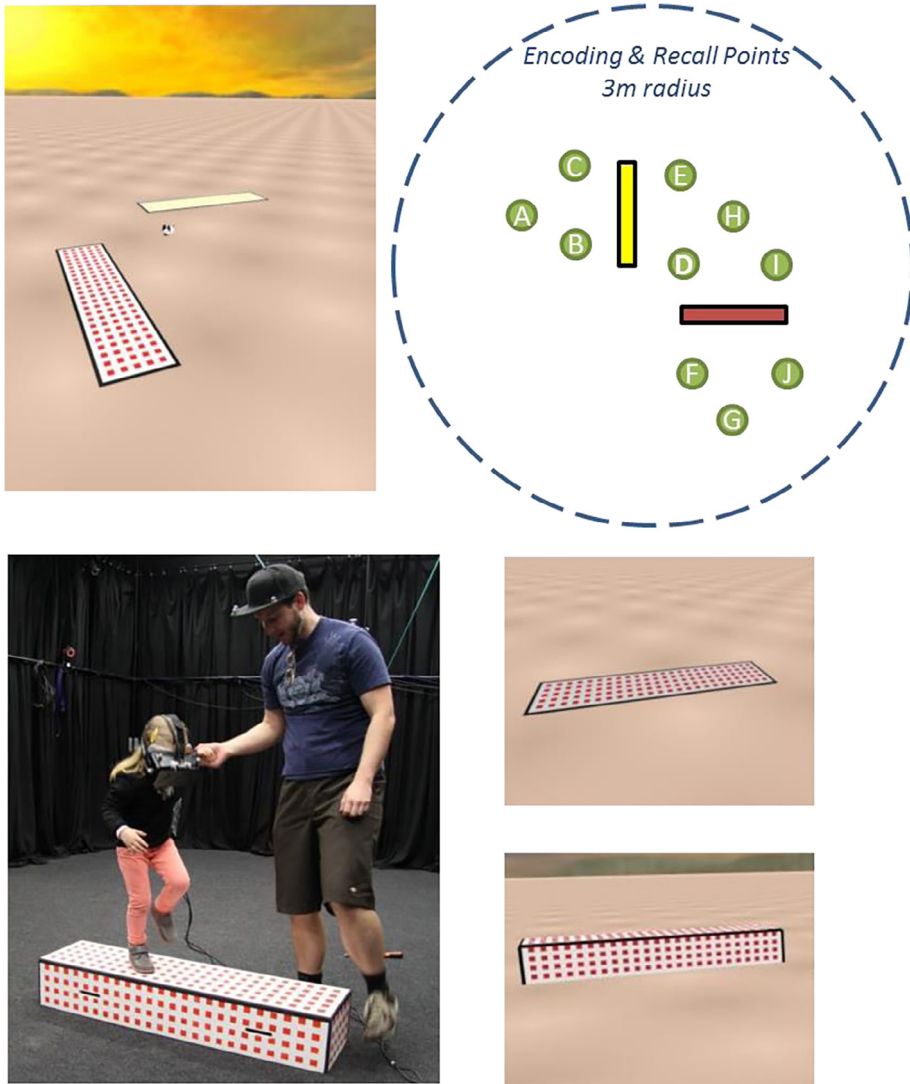
Fig. 1. This was the virtual environment. Top left: Screenshot of the target item (mouse) and the two 2D landmarks. Top right: Diagram of the target locations plus the invisible circle of viewing points where participants stood while encoding targets and responding. Rotation magnitudes were in random order, and the view was not reset between trials, so they could encode or recall from nearly any point on the circle. Bottom left: Photograph of a participant interacting with the actual 3D box. Bottom and middle right: Comparison of the 2D versus 3D landmarks.

four targets near the remaining corners of the two landmarks (B, E, F, and I) shared 8 trials evenly. There was one block per condition (2D vs. 3D) totaling 48 usable trials per child. The possible rotations were 30, 40, 50, 60, 105, 125, 145, and 165 degrees. The teleportation was to the left in half of the trials and to the right in half of the trials.

Rotations were counterbalanced across targets so that each of three target categories—in the middle and its reflections, on minor axes and its reflections, and the remaining corners—were sampled at less than 90 degrees half of the time and at more than 90 degrees half of the time within each block and so that rotations were used evenly but otherwise random. Condition order (2D vs. 3D) was

counterbalanced across participants, but all participants saw both conditions. Within each block, no two trials in a row had the exact same target, but the order was otherwise random. The direction of the teleport was even within each block but was otherwise random.

Procedure

Warmup

Before the 2D condition, participants were instructed to walk over the flat red landmark. Before the 3D condition, participants stepped onto (Fig. 1) and jumped off of the red 3D landmark (box) with the experimenter, both inside and outside of the virtual reality. Once the headset was fitted, participants were shown how to point accurately at the target and were given 4 trials to practice. They were required to point within 50 cm to continue. It was also demonstrated that they would need to remember the location of the target after it had "dug" underground. Participants were given another 4 trials with the same criterion. Finally, they were shown the teleportation. This was done by fading the screen to black, moving the rendering camera, and then fading back up again. This proceeded from small teleports to longer ones, with a green cross indicating where they were going before each trial. The experimenter drew special attention to the green cross and emphasized that nothing in the environment would move except for the participants, their "teleporter," and the experimenter. The experimenter avatar "teleported" along with the children so as not to serve as a useful spatial reference. The data collection trials were introduced by telling participants that the rest of the game would be just like the last trial except that they would not have a green cross to tell them where they are going first.

Data collection trials

On each trial, the mouse appeared from underground (it never moved across the surface) and participants were allowed to view it as long as they wanted. The mouse would then "dig" underground, leaving no visible trace of its location, and participants would be teleported to a new position around a 3-m radius circle. That circle's center was denoted as (0, 0) in the program, with the center of the two landmarks laying at (−.3125, 0.625) and (.9375, −0.625), so the center of rotation was offset by about 30 cm from the in-the-middle target. That circle itself was never shown explicitly to participants. The view rotated as well, so a child facing left of the center before teleportation would still be facing left after. The total teleport time was about 2.5 s (plus or minus screen refresh time) regardless of the distance of the teleport. Participants would then point to where they thought the mouse was using the motion-tracked "wand." A response was recorded when the pointing was stable over a period of 2 s. At this point, the mouse would reappear at its previous location and the experimenter would give verbal feedback (e.g., "Good job, it was by the red one, on that side, and on that end!" for a correct or nearby response, "Hmm, it was on that side, but it was on the other end" for an incorrect response). After giving this feedback, the mouse again dug underground. The view was not reset; the encoding viewpoint for the next trial was the recall viewpoint for the last trial.

A break was given between testing blocks (plus any more requested by participants). At the start of the second block, the new landmarks were introduced (i.e., they walked over the flat red landmark or stepped onto the red 3D landmark), but the other warmup trials were not repeated.

Results

First, we checked that performance was above chance for the youngest group as expected. Using the bootstrapping analysis from our previous work (Negen et al., 2017), all 15 children in the youngest age group scored above the expected chance level. They were significantly above chance as a group, $p < .001$, and 11 of them were significantly above chance as individuals (remaining ps = .10, .44, .13, and .25). All of the older children were significantly above chance as individuals as well. Having met the goal of eliciting allocentric spatial recall from each of the age groups, we proceeded with the planned analysis.

We chose to work with the raw error (distance from response to correct location) transformed into log units because the raw errors deviated strongly from a normal distribution. In the next sections, we

use an analysis of variance (ANOVA) approach to look for two expected control effects, specifically an ordered age effect and a rotation effect, because we would doubt the validity of the task without these. This ANOVA also lets us look for age interactions to determine the best way to deal with the two hypothesized effects. Afterward, we examine the effect of 2D versus 3D landmark types with the same ANOVA calculations and some follow-up analyses, hypothesizing a 3D advantage. Following that, to test whether there was a hypothesized in-the-middle advantage, we use the ANOVA results and supplement them with sensitivity/specificity analyses and a modeling method.

Expected effects of age and rotation

Because age group is the only purely between-participants variable in the design, we looked at it separately first. We calculated an average score for each child. A one-way ANOVA found a strong expected effect of age group (4.5–5.5, 5.5–6.5, or 6.5–8.5 years), $F(2, 45) = 24.1165$, $p < .001$, demonstrating a developmental decrease in log-error. There was a significant repeated contrast for the younger versus middle group, $p < .001$, and the middle versus older group, $p = .046$. Following this, we ran a 3 (Age Group) × 8 (Rotation Level) × 10 (Target Location) × 2 (Landmarks: 2D or 3D) × 2 (Testing Block: first or second) ANOVA as our main analysis.[2] See Fig. 2 for a general overview of the results and Table 1 for a full listing of the ANOVA calculations.

As expected, larger rotations led to larger average log-error. We also found the effect of age group again. Therefore, both expected effects were present in the expected direction, which we interpreted as evidence that the task was sensibly measuring spatial recall performance.

2D versus 3D performance

We did not find a main effect of 2D versus 3D landmarks. We did, however, find both a main effect of testing block, with lower log-error in the second block (0.66 vs. 0.59 m), and an interaction between landmark type and testing block. A pair of post hoc t tests with a Bonferroni correction showed a significant effect of landmark type in the second block, $t(1150) = 3.1743$, $p = .0015$, but not in the first block, $t(1150) = 0.0848$, $p = .9325$. As such, we not only failed to find a hypothesized advantage for 3D landmarks but instead found a possible advantage for 2D landmarks that seems to require a level of familiarity with the task to emerge—although this should be interpreted with caution because the main effect of landmark type was not significant. There was also no significant interaction with age group (0.84 m in 2D vs. 0.93 m in 3D for 4.5- to 5.5-year-olds, 0.53 m in 2D vs. 0.63 m in 3D for 5.5- to 6.5-year-olds, and 0.48 m in both 2D and 3D for 6.5- to 8.5-year-olds).

We wanted to be sure that the pragmatics of pointing were not masking an actual 3D advantage. To check whether this interaction effect is driven by the 3D boxes blocking the view of children's response on some trials, we looked at the subset of trials where the target was on the same side of all the landmarks as the children when they were responding. The results were similar; there was no significant effect of block or landmark type, $ps = .8369$ and $.3192$, but the same interaction appeared with lower average log-error for 2D landmarks than for 3D landmarks in the second block, $F(1, 703) = 6.2182$, $p = .0129$. It is not clear why the block effect was not significant, but one simple explanation is the reduction in statistical power. On balance, this suggests that the 3D landmarks occluding children's view is not the main reason why 2D performance was better in the second block.

A number of supplementary analyses were also performed. These were variations on the primary ANOVA (e.g., including the distance between the recall viewpoint and the target as a factor) and a bootstrapping analysis to look at the spatial layout of responses in the 2D versus 3D conditions.

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[2] We considered a repeated-measures or mixed-model analysis as our primary analysis but ultimately decided to present it as a secondary analysis in an appendix. The study was designed to give us a wide sampling of targets, rotations, blocks, and landmark types inside each age group. However, there were 10 targets × 8 rotations × 2 blocks × 2 landmark types, meaning that each child could encounter a total of 320 experimental conditions. Each child's actual dataset has 48 non-warmup observations that were sampled systematically across that possible space. As such, a repeated-measures approach would be either explicitly (e.g., multiple imputation) or implicitly (e.g., converting to z scores or entering a participant variable) inferring most of the data. We also limited results to main effects and two-way interactions for similar reasons.
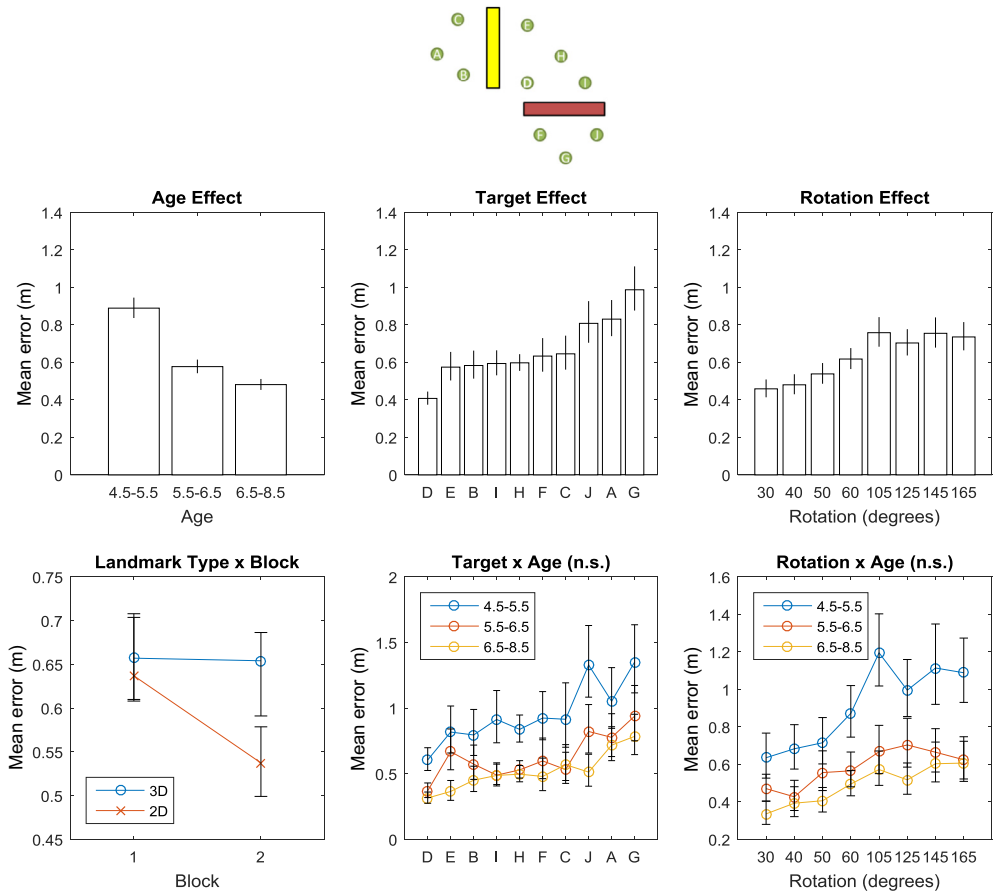
Fig. 2. All scales on the *y* axis have been reconverted to linear units (after being averaged in log units). Bars are 95% confidence intervals calculated independently for each bar. There was a strong age effect (top left), a strong target effect (top middle), a strong but slightly nonlinear rotation effect (top right), an interaction between landmark type and block with an accompanying main effect of block but not landmark type (bottom left), and no interaction between age and either target (bottom middle) or rotation (bottom right).

Because the findings did not change our interpretation of the results regarding our main hypothesis, we provide them in Appendixes B to F for any reader who may be interested in the additional details.

Looking for an in-the-middle effect

There was a strong main effect of target location (see Table 1) that did not interact with age. Our interest was not just in a general target effect but specifically in an advantage for the target in the middle. Fig. 3 provides a map of the varying performance levels, confirming that the in-the-middle target did indeed have the least log-error. These results so far are consistent with the hypothesis that targets in the middle (target D) are easier to remember. It also speaks to the sensibility of our measure that targets farther from the landmarks generally had higher log-error (Fig. 3).

From the ANOVA above and Fig. 3, it is already clear that participants were more accurate when they were asked to point at target D, which falls most clearly in the middle (i.e., the one that is on the center point of a line segment joining the center points of the two landmarks). However, does this

Table 1

ANOVA to test expected age and rotation effects plus hypothesized 3D advantage (landmark type) and in-the-middle advantage (target) and interactions.

	df	SS	F	η^2	p
Age group	2	150.58	115.833	.079	<.001
Landmark type	1	0.83	1.283	.000	.258
Block	1	4.84	7.445	.003	.006
Target	9	135.54	23.169	.071	<.001
Rotation	7	96.08	21.117	.051	<.001
Age group * Landmark type	2	0.69	0.531	.000	.588
Age group * Block	2	3.24	2.492	.002	.083
Age group * Target	18	18.64	1.593	.010	.054
Age group * Rotation	14	6.49	0.713	.003	.763
Landmark type * Block	1	18.43	28.350	.010	<.001
Landmark type * Target	9	4.18	0.714	.002	.697
Landmark type * Rotation	7	4.75	1.044	.002	.398
Block * Target	9	4.41	0.754	.002	.659
Block * Rotation	7	2.86	0.628	.002	.733
Target * Rotation	63	48.34	1.180	.025	.159
Error	2151	1398.11			
Total	2303	1899.78			

Note. Significant effects are in bold. The significant effects in order of largest to smallest effect size are age group, target, rotation, Landmark Type * Block, and block.
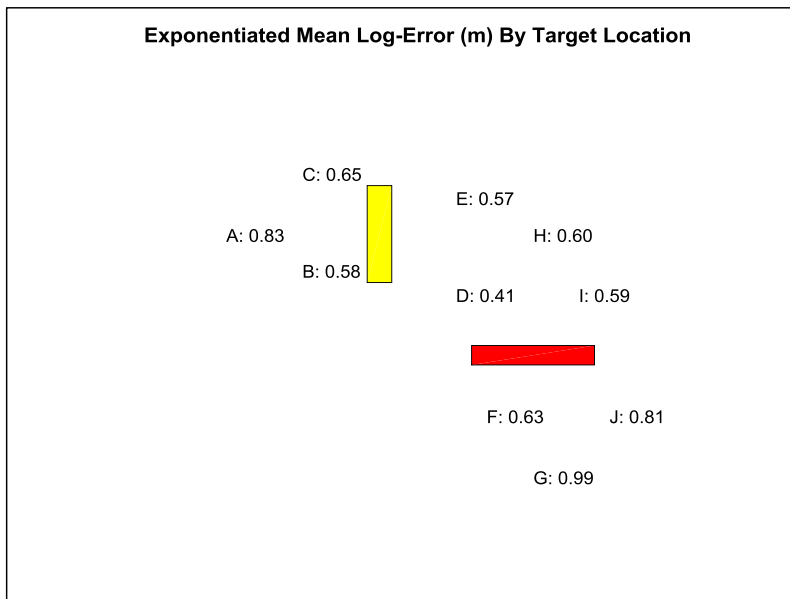
Fig. 3. Error at each of the 10 target locations (in meters) after taking the average of their logarithm and exponentiating them. The target D in the middle had the lowest average log-error, as we hypothesized.

necessarily mean that they were better at remembering that a target was there? Is it possible that some other process is creating this effect?

To find out, we considered whether there was an overall preference to point near the in-the-middle target, D, regardless of the correct target. Table 2 shows what percentage of responses fall nearest each target's location for each actual target. The numbers down the diagonal are the rate of correct responses. If all errors were randomly placed on other target locations (e.g., they were just as likely

Table 2
Confusion matrix between the targets and the target that responses were nearest.

		Response										
		A	B	C	D	E	F	G	H	I	J	Sum
Target	A	**20**	33	18	8	5	6	2	2	3	1	100
	B	5	**48**	13	11	7	3	1	4	4	2	100
	C	4	26	**41**	6	7	3	3	5	2	2	100
	D	1	5	2	**65**	6	6	1	7	6	2	100
	E	3	7	5	24	**41**	5	0	7	5	1	100
	F	3	9	4	10	1	**45**	6	4	5	13	100
	G	3	4	4	7	3	31	**18**	5	7	17	100
	H	2	5	2	22	14	4	2	**36**	13	2	100
	I	1	2	2	24	3	6	2	12	**41**	5	100
	J	2	3	4	11	6	23	5	3	8	**33**	100
Sum		46	142	96	189	93	132	43	86	96	78	

Note. Values are percentages.

to point at all four corners of the red box when they were not sure), then the columns all should sum to about 100%. The in-the-middle target, D, sums to 189%, and the two closest to it (targets B and F), across the major axes of the two boxes, are at 142% and 132%. The two farthest from the landmarks sum to 43% and 46%. This shows that responses are systematically biased to be toward the center of the arena in this dataset. This is a potentially serious issue for the interpretation of better performance on the in-the-middle target. As an extreme example, imagine that children remembered and pointed directly to the correct location 50% of the time, but for the other 50% of the time they pointed directly at the in-the-middle target. The accuracy at that one target would be 100%, and the accuracy at all others would be 50%, despite the fact that they are not genuinely any better at remembering targets there. Diagnostic of this would be a very high false positive rate, where children pointed to the in-the-middle target when it was not actually there.

To get a closer look at this issue, we started by examining sensitivity, specificity, and positive predictive value (see Table 3). Sensitivity (true positives/[true positives + false negatives]) was the highest at the in-the-middle target, D. However, specificity (true negatives/[true negatives + false positives]) was the lowest for that target, and the positive predictive value (true positives/[true positives + false negatives]) for that target was in the middle of the range. In other words, participants did not do better at that target on metrics that specifically punish pointing at that target when the target is not actually there. However, this does not necessarily mean that they were not *both* tending to point very often at the in-the-middle target when unsure *and* more likely to remember when that was the correct location to recall; to look for that, we needed a method to separately assess participants' memory precision and their tendencies to guess in different places.

We used a Bayesian cognitive model to separately estimate the contributions of biased guessing behavior and an unbiased memory recall process. The model assumes that every trial is completed by either a guessing process or a memory process. When using the guessing process, responses are completely unrelated to the target, but the preference to guess near different targets is allowed to vary (a multinomial distribution with 10 possible outcomes). When using the memory process, the chance of pointing to each target is a function of how close it is to the correct target (subject to exponential decay), with farther targets being less likely. This is controlled by a precision parameter. An additional parameter controls how often each process is used. Before fitting to the data, there is no built-in bias toward any particular rate of using the memory process or in favor of any particular place to prefer guessing. Details and code appear in Appendix A. The results are presented in Fig. 4.

The model fit was good overall, with a correlation between predicted confusion matrix and observed confusion matrix of $r = .90$. The posterior mean memory rate was about 2/3; the model inferred that for every trial where participants guessed (i.e., responded in a way that was totally unrelated to the target), there were about 2 trials where they remembered (with some imprecision, of course).

Table 3
Sensitivity, specificity, and positive predictive value by target.

	A	B	C	D	E	F	G	H	I	J
Sensitivity	0.20	0.49	0.43	**0.67**	0.43	0.46	0.18	0.36	0.43	0.34
Specificity	0.98	0.91	0.95	**0.85**	0.94	0.91	0.98	0.95	0.93	0.96
PPV	0.45	0.32	0.43	**0.48**	0.38	0.32	0.42	0.57	0.37	0.42

Note. "In the middle" is in bold. PPV, positive predictive value.
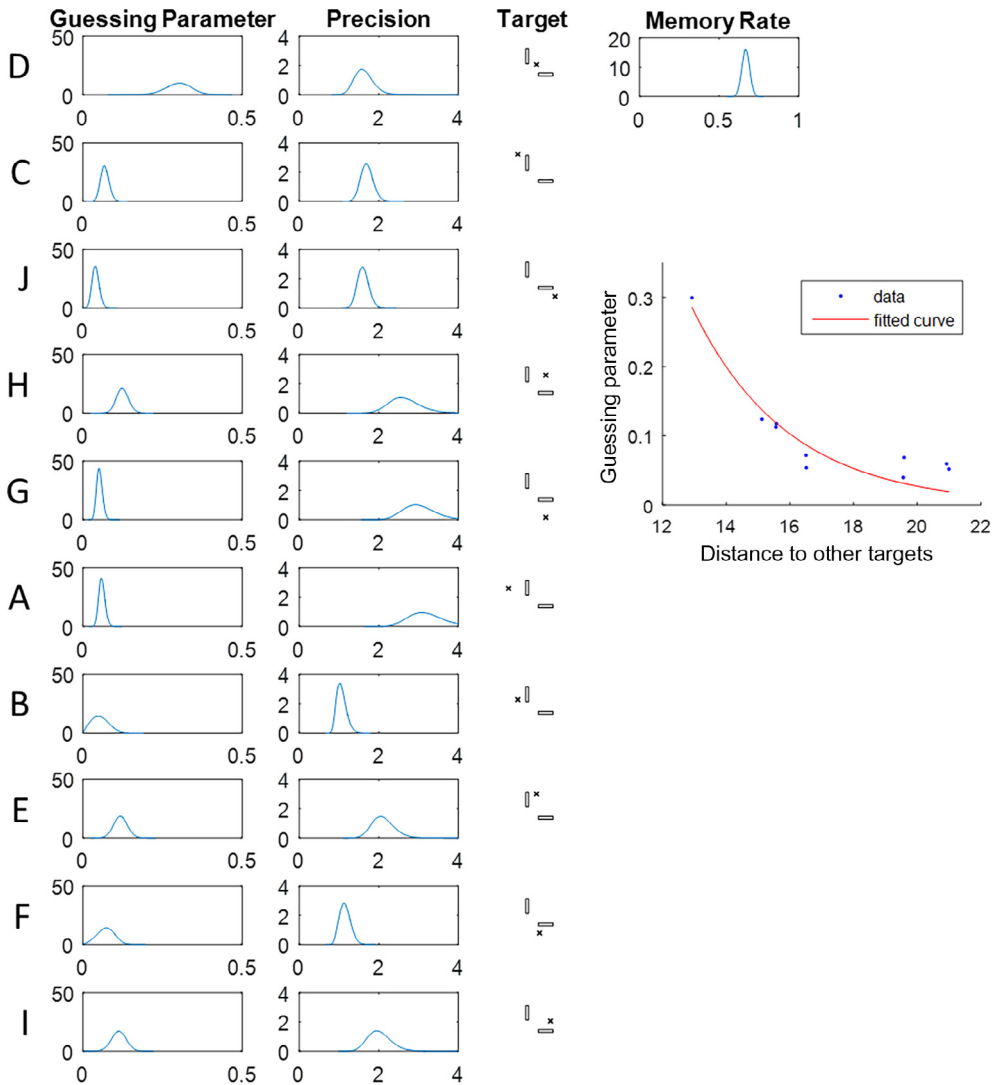
Fig. 4. Posterior distributions over model parameters. The guessing parameter is predicted roughly as an exponential curve of the average distance to all other targets (i.e., how good of a guess it is with no trial-specific information). The precision is largely in three clusters that correspond to the nature of the geometric relation to the two landmarks (e.g., highest precision when they are on a minor axis of at least one landmark) and not particularly to which targets are in the middle.

When using the guessing process, children seem to be guessing at the in-the-middle target much more often than any other target, roughly 35% of the time (as seen by looking at the peak of the distribution for target D in the guessing parameter column of Fig. 4). This is a sensible strategy for guessing because it is the point that minimizes average error over all possible targets. Indeed, there is a roughly exponential relation between the posterior means of the guessing parameters and the average distance to all of the other targets.

The critical results in terms of actual memory precision do not support the expected advantage for a target in the middle. The posterior distributions over memory precision fall into roughly three clusters (sets of posterior distributions with a reasonable level of overlapping concentrations). A higher precision means that participants were more likely to point at the correct target and that the drop in probability of pointing is steeper as targets became farther from the correct target. As one scans down the precision column of Fig. 4, there are three distributions that are farther right. Those are the three targets with the greatest distance to a landmark (A, G, and H), which had the highest precision. The trials including the in-the-middle target and its reflections over the centers of the landmarks plus the other two targets on the interior near the landmarks (C, D, E, I, and J) had the next highest precision, falling down the center of the precision column. The two targets that were outside the landmarks and not a reflection of the in-the-middle target over the landmark centers (B and F) had the lowest precision, falling to the left. In short, there was not any consistent measurable advantage in terms of memory precision for the target that was in the middle (D) or generally for targets on the interior of the landmark array versus the exterior (e.g., A and G vs. H). Instead, it seems that the best precision is found on the minor axes of the two landmarks, followed by targets that at least lay on an intersection of lines through two edges of the landmarks.

The reader may also have some intuition that target H would be classified by some as in the middle, but the results for that target are not particularly good evidence for an in-the-middle advantage either. It did not score highest in accuracy, sensitivity, or specificity, and the associated posterior distribution for its memory precision overlaps heavily with both A and G (which are clearly non-middle), with H having the lowest mode of the three. It did have the highest observed posterior predictive value, but it is not clear whether this reflects any genuine memory advantage.

In summary, the modeling analysis, which allowed us to separately estimate the tendency to guess near certain targets and the precision of memory, suggests that apparent advantages for the in-the-middle trials are potentially an artifact of a biased guessing process rather than evidence of a genuine advantage in terms of spatial recall.

Appendix G shows the results from applying the model to each of the three age groups separately, and they do not show any particular difference that would change our main interpretation here; the memory rate and the precision parameters all generally increased with age, but the pattern of high guessing and middling precision for target D remained the same.

Discussion

The first expected effect—that all age groups would perform above chance when forced to use allocentric representations to recall locations—was supported by the data in line with our previous work (Negen et al., 2017). Children aged 4.5 years and over were able to systematically use allocentric representations, independent of any egocentric strategies during spatial recall, despite the potentially disruptive effects of encoding soon after losing orientation (e.g., Knierim, Kudrimoti, & McNaughton, 1995). Yet, neither of the two factors that we expected to moderate performance had compelling effects. Based on the analysis conducted, there were three opportunities to find an advantage for 3D landmarks over 2D landmarks, but none of them followed the trend in the predicted direction. We actually found a significant post hoc advantage for the 2D landmarks in the second testing block. We did find an accuracy advantage for the target that was in the middle, but when we applied a modeling method to separate out memory precision and tendency to guess at different targets, the result is that in the middle is a common place to guess and is not subject to an especially high memory precision. The effect of these two parameters did not interact significantly with age, and the model results

do not suggest any major shift in how target locations differ when the model is applied to each age group separately. Thus, these effects appear to be relatively consistent from 4.5 to 8.5 years of age.

Placed together, these results emphasize how different and separate allocentric spatial memory during middle childhood is compared with navigation during early childhood and in other species such as mice. Based on studies of neural encoding and reorientation behavior (which is a navigation task), we predicted a 3D advantage but actually found a (limited) 2D advantage. Based on studies that have shown trends in navigation results in 2- to 5-year-olds, plus early language development, we predicted a memory precision advantage for targets that could be described with the short phrase "in the middle," but we found it to have middling memory precision. The only consistency is a tendency to bias responses toward the target in the middle, which is generally consistent with category adjustment models (e.g., Huttenlocher et al., 1991) rather than specific developmental navigation systems. This suggests that allocentric spatial recall during middle childhood may rely on fundamentally different mechanisms from those underlying seemingly related tasks such as reorientation and early linguistic spatial encoding. This kind of allocentric spatial recall also seems not to make use of neural representations of space related to boundaries that we currently know about from animal and human (adult) studies.

2D versus 3D landmarks

The first expected effect—that 3D landmarks would be more useful than 2D landmarks for children at 4–8 years of age—found no support in our data. We considered whether a 3D advantage may be present but masked by simple pragmatics of the task. The 3D boxes have some height and, thus, occlude a little bit of the surface of the response area. This means that sometimes children might want to respond somewhere that they cannot see, which may be less accurate. However, the interaction effect and the trend in means remained the same when we excluded trials where children were not on the same side of the landmark as the target, making that explanation unlikely.

A 2D advantage was evident only during the second testing block, and it is not entirely clear why this advantage occurred. It could be a simple Type II error in the first block, or it could be a more complex phenomenon such as building up a useful prior over the spatial layout of targets that is easier to apply in the 2D landmark case. A third possibility for a 2D advantage in the second testing block is that sometimes simplicity is vital. The 3D landmarks include a greater number of surfaces to which locations could be referenced (vertical as well as horizontal). Because the experiment was done in fully immersive virtual reality, they also provide potentially richer information about their own spatial layout, for example, via stereopsis and motion parallax. In other contexts, young children fail to consistently select the most informative spatial references (Nardini et al., 2006; Negen & Nardini, 2015) and fail to judge spatial layout by appropriately combining multiple available cues to depth (Dekker et al., 2015; Nardini, Bedford, Desai, & Mareschal, 2010). It is possible that immaturities in selecting and combining the available information appropriately meant that the additional information masked the useful signal with unnecessary noise on some trials. It would be interesting to test whether the additional 3D information starts to advantage spatial precision at older ages.

The difference in terms of 3D advantage between this task and reorientation tasks could be dependent on at least three specific factors: (a) the nature of the spatial cognition being demanded, (b) the nature of the response given, and (c) the age range. For the first factor, reorientation tasks are possible to complete in principle by some kind of view matching (Stürzl et al., 2008), although there is evidence that depth processing is involved (Lee, Winkler-Rhoades, & Spelke, 2012), so it would need to be a 3D "view" (likely excluding some features other than 3D surfaces) rather than a 2D view (like a typical camera would record). For the second factor, we allowed children to make a continuous response anywhere in the region around the landmarks via pointing (to prevent egocentric information from being gathered during movement) while they stood in one place. Reorientation tasks typically allow children to move themselves to one of four possible predetermined responses, two of which are perceptually identical. An advantage for 3D information may assert itself while moving via mechanisms such as motion parallax. Although it does appear that children rarely change their minds once they start moving toward a corner in those tasks. It is also possible that pointing puts a higher executive function load on the participants (because movement must be inhibited and the decision space is larger) or is more

related to additional individual differences such as mental rotation skills (e.g., Shepard & Metzler, 1971). Furthermore, the typical reorientation task effectively eliminates a large range of possible responses for children, and it is not clear what effect this has. For the third factor, the age range tested here is older than that in most reorientation studies. However, our age range does overlap somewhat with one study that found a 3D advantage (Lee & Spelke, 2008) and we did not find a landmark type by age interaction, so that may not be the correct explanation. Additional research would be needed in order to clarify exactly which factor(s) is (are) necessary to cause the difference in behavioral patterns.

These results also bring up questions about how to interpret functional magnetic resonance imaging (fMRI) studies with adults. Ferrara and Park (2016) found that the retrosplenial cortex (RSC) is specifically responsive to the presence of "walls" (~47 cm in height) instead of "curbs" in a visual display, providing supporting evidence for a neural representation of boundaries. This is taller than the 3D landmark we showed the children, but those children are also significantly shorter than the adults, especially the youngest children, so it is likely to represent a comparable impediment to movement (at least under purely visual analysis). This brings up questions about what that coding in RSC is used for, whether it appears earlier in life, and whether it is sensitive to the same parameters (scaled or unscaled to participants' height). It would also be useful to understand how this interacts with developing hippocampal neurons (e.g., Wills & Cacucci, 2014). Moving that type of study into development could be very productive.

In-the-middle targets

The second expected effect—that there would be an advantage of being "in the middle," was supported by a first-approximation look at raw error rates but can likely be explained by strategic or prior processes rather than actual superior memory. We found no particular memory advantage for the target in the middle after accounting for the biased guessing behavior. We fitted a Bayesian cognitive model with a separate memory and guessing process to the data. The rate of guessing around the in-the-middle target was very high, around 35%, but the memory precision was clearly lower than all three targets that were farther from the landmarks, including two that were not even between the two landmarks. The precision parameter for each target is potentially explained by the availability of convenient placement in line with the axes and edges of the two landmarks. It does not, however, have any apparent effect of being on the interior of the two landmarks or ease of naming; one target that is on the side of the red box farther away from the yellow one has much higher precision than the target that is in the middle (or even "near the corner"). As such, we cannot interpret the findings here as evidence that 'in the middle' is an easier spatial recall problem at this age despite the many reasons to hypothesize that it might be.

The correct broader interpretation of the bias toward the center could take several forms. It could be an effect that is specific to this task and context such as an explicit strategy; the target in the middle is generally the best place to guess if one can estimate the distribution of targets over the course of the experiment. It could even be a simple prior belief that a mouse would typically prefer to hide near scene features rather than in a relatively barren stretch of an environment. The bias found here could reflect something larger and less specific to this task as well. This could be an example of an extreme category adjustment effect (e.g., Huttenlocher et al., 1991), where the center serves as a prototype for categorical knowledge (e.g., "it was near the landmarks").

Many of the questions about 'in the middle' could be clarified a great deal by studies that present younger children with the opportunity to navigate to a target in the middle and to targets elsewhere in otherwise identical settings. A simple bias to respond in the middle, found here, could explain some of the effects described in the Introduction. Three navigation studies have trained children to respond in the middle in one set of task parameters and then observed them responding in the middle after those parameters change (Ankowski et al., 2012; Sims & Gentner, 2008; Tommasi & Giuliano, 2014). However, they did not train any children to respond anywhere else, and they did not test what children would do without the training. It is not clear whether their posttraining behavior reflects the generalization of learning during the training rather than a bias to respond in the middle in a new situation. Examining children's biases and priors in spatial memory tasks with different geometries and contexts, and also how children evolve with experience in each particular task at different ages, could

be a fruitful line of future research. More generally, an understanding of how guessing behavior functions should be of interest for a wide variety of cognitive and perceptual tasks (Jones, Kalwarowsky, Atkinson, Braddick, & Nardini, 2014).

Impact on theory

Taken as a whole, these results highlight the incompleteness of our theories of how the whole of spatial cognition develops and functions in humans. We were not able to produce a novel, testable, verified prediction about allocentric spatial memory during middle childhood from (a) the study of early navigation performance, (b) the study of mammalian spatial neurons, or (c) the study of early spatial language development. An account of the detailed behavioral characteristics of developing allocentric spatial memory during middle childhood may need to be built from first principles rather than relying on those other areas of study for similarities. For example, we found that some targets were remembered with greater precision than others, but our explanations for why those specific targets were remembered better all are post hoc.

To explain the cognitive processes involved in allocentric spatial memory, we may need to look to areas of study that are not traditionally classed with navigation behavior under the broader umbrella of spatial cognition. It could possibly be more related to mental rotation (e.g., Shepard & Metzler, 1971), for example. This certainly fits with the finding that rotation had a strong effect that did not interact with age, although the effect does seem to decelerate at more than 105 degrees in the current dataset rather than remain linear (see Fig. 2). It is also unclear whether there is something specific about the details of the task that make it similar to mental rotation in that aspect or whether that would generally be found in any similar task. Another possible example is the process of scene perception (e.g., Henderson & Hollingworth, 1999), which occurs largely in brain regions outside of the hippocampus (e.g., O'Craven & Kanwisher, 2000). Generally speaking, however, studies in that area deal with recognizing similar scenes from different perspectives, often focusing on how saccades and other eye movements find the relevant features for recognition rather than classing points inside the scene by their relative accuracy, so it also is not clear how to explain these data with those theories. A third example is a kind of categorization process (e.g., Shafto, Kemp, Mansinghka, & Tenenbaum, 2011), although we would also need a theory of how 3D spatial relations are computed to be the inputs of the categorization. In general, it is possible that we should be analyzing allocentric spatial memory during middle childhood as a case of discontinuous conceptual development (e.g., Carey, 2004, 2009; Spelke, Lee, & Izard, 2010), although it will require much further study to determine that conclusively.

Future study

To continue examining this quandary, we suggest further study to identify the factors that explain differing levels of performance in terms of allocentric spatial recall during this period of development. The model results suggest that geometric convenience is a potential factor, that strategic or prior choices have a strong influence on overall behavior, and that being interior versus exterior to the array is not largely relevant for the actual memory component. Knowing more about what kind of landmarks or landmark arrays are superior, the potential relevance or irrelevance of strong orienting cues, the influence of cognitive factors such as executive function, and even results of similar tasks in other age ranges could help to gain insight into the development under examination here. In studying this, we encourage other researchers to ideally use modeling methods to explicitly remove the effect of biased guessing behavior, or at least to examine sensitivity and specificity, because these can reveal patterns that are quite different from, and more nuanced than, raw accuracy. We still know only a few facts about what behavioral features need to be included in an accurate model of how allocentric spatial memory functions during middle childhood.

Appendix A. Details and code for the Bayesian model analysis

The WinBUGS code (Lunn, Thomas, Best, & Spiegelhalter, 2000) is presented in Fig. A1. Each target was assigned a number 1–10, and the data were preprocessed so that responses just indicated which target they pointed nearest. Five chains were run with 2000 burn-in samples and 20,000 recorded samples. The guessing probability weights were each given a Gamma(2,1) prior and then divided by their sum to calculate the guessing probability, which means that they all have a mode at 10% and some positive probability density all the way from 0% to 100%. The precision parameters were also all given a Gamma(2,1) prior, meaning that the prior mean response distance is 1 m from the target when using the memory process. Informal experiments did not suggest that there is much sensitivity to these priors in relative terms; changing the priors will shift all of the posterior distributions in absolute terms, but the posteriors remain in the same order.

We also wanted to see whether there were any obvious biases in how this model predicts data versus the actual data. We took a probit transform of the actual response rates minus a probit transform of the predicted response rates (Table A1) and looked for patterns. We did not find any in particular. One might, for example, expect that reflections over the center point of the local landmark would be more common than our model (which provides no special increase in probability for that) would predict. That would be the pairings of A–E, C–D, D–J, and F–I. However, there were actually fewer responses with target A at E than expected and similarly for C at D, for D at C, for D at J, for J at D, for F at I, and for I at F. One might also expect that reflections across the single line of symmetry of the unified scene would be underpredicted by our model. That would be A–G, B–F, C–J, and E–I. However, there were fewer responses than predicted for F at B, for E at I, and for I at E. The largest inaccuracies were the overprediction of correct target selection, so it is possible that the model could be improved slightly by changing the function that relates distance to predicted accuracy to be lower at the closest actual target and to slope more gradually. However, it does not appear that any major issues have arisen that would place significant doubt on the large trends in the results.

Appendix B. Percentage correct

We also looked at a discrete measure of performance: how often the response was nearer to the actual target than any of the other target locations. This yields a "proportion correct" score (note that the alternative target locations are used for scoring, but in practice participants are never making a choice among the 10 locations). This measure could be less powerful, but it also has some potential advantages. The main analysis of distance error is underpinned by the assumption that performance depends on the precision of spatial recall. However, when a location is completely forgotten or misplaced due to incorrect use of a landmark and/or an "egocentric" error, the amount of distance error is not meaningful. Table A2 presents an ANOVA over proportion correct with largely agreeing results: a main effect of age group, target, and rotation amount plus a Landmark Type × Block interaction.

The differences are the nonsignificant effect of block and a significant Age Group × Target interaction; the main thing driving this is that the younger children had more difficulty in distinguishing the in-the-middle target from the other targets along the interior of the landmarks. There is still no significant effect of landmark type. Fig. A2 shows the mean proportion correct in the same arrangement as Fig. 2 in the main text, with the note that higher scores are better in terms of percentage correct, and the other figure displays error, where higher scores are worse.

```
model{
memoryRate ~ dbeta(1,1)
for (i in 1:10){
    guessWhichTmp[i] ~ dgamma(2,1)
    guessWhich[i] <- guessWhichTmp[i] / sum(guessWhichTmp[1:10])
    precision[i] ~ dgamma(2,1)
    for (j in 1:10){
        memoryChooseTMP[i,j] <- exp(-Distance[i,j] * precision[j])
        memoryChoose[i,j] <- memoryChooseTMP[i,j] / sum(memoryChooseTMP[i,1:10])
        p[i,j] <- memoryRate * memoryChoose[i,j] + (1-memoryRate) * guessWhich[j]
    }
    responses[i,1:10] ~ dmulti(p[i,1:10], N[i])
}
}
```

Fig. A1. WinBUGS code for the modeling analysis.

Table A1
Probit of actual response confusion matrix minus probit of model posterior predictive.

	A	B	C	D	E	F	G	H	I	J
A	**−0.89**	0.11	0.06	−0.39	−0.04	0.15	0.06	−0.30	−0.11	0.00
B	−0.19	**−0.37**	−0.10	−0.43	−0.06	−0.38	−0.14	−0.09	−0.07	0.09
C	−0.11	0.05	**−0.52**	−0.58	−0.11	−0.19	0.13	−0.04	−0.37	0.19
D	−0.29	−0.53	−0.39	**0.19**	−0.27	−0.40	−0.17	−0.14	−0.25	−0.38
E	0.13	−0.31	−0.29	−0.04	**−0.37**	−0.08	−0.53	−0.33	−0.24	−0.31
F	0.08	0.04	0.02	−0.44	−0.63	**−0.39**	−0.22	−0.09	−0.25	−0.06
G	0.15	−0.07	0.11	−0.45	−0.15	0.11	**−0.95**	−0.01	0.11	0.04
H	−0.12	−0.21	−0.32	−0.01	0.01	−0.30	0.08	**−0.27**	−0.05	−0.28
I	−0.19	−0.44	−0.29	−0.03	−0.42	−0.38	0.02	−0.07	**−0.37**	−0.23
J	−0.08	−0.14	0.11	−0.25	0.13	0.02	−0.12	−0.19	−0.12	**−0.65**

Note. Negative values indicate overprediction.

Table A2
ANOVA over percentage correct.

|	df	SS	F	η^2	p
Age group	2	23.197	56.930	.041	<.001
Landmark type	1	0.013	0.064	.000	.800
Block	1	0.604	2.965	.001	.085
Target	9	45.246	24.676	.081	<.001
Rotation	7	16.829	11.801	.030	<.001
Age group * Landmark type	2	0.106	0.260	.000	.771
Age group * Block	2	0.099	0.243	.000	.784
Age group * Target	18	6.162	1.680	.011	.036
Age group * Rotation	14	4.155	1.457	.007	.119
Landmark type * Block	1	2.640	12.959	.005	<.001
Landmark type * Target	9	1.345	0.733	.002	.679
Landmark type * Rotation	7	2.410	1.690	.004	.107
Block * Target	9	0.780	0.425	.001	.922
Block * Rotation	7	1.636	1.147	.003	.330
Target * Rotation	63	15.430	1.202	.028	.135
Error	2151	438.236			
Total	2303	560.822			

Note. Significant effects are in bold.
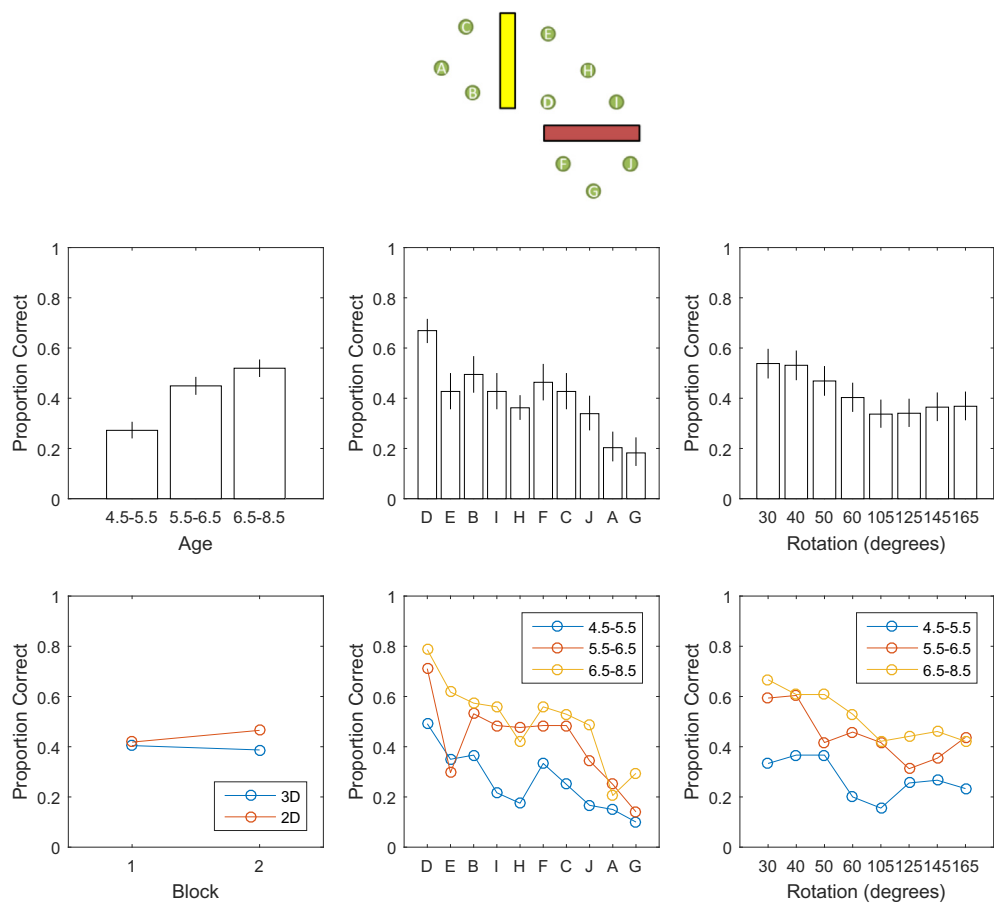
Fig. A2. Results in terms of proportion correct.

Appendix C. Primary ANOVA with participant as a variable

Our choice of a primary analysis without any repeated-measures component may seem unusual to the reader, so we also present an analysis where we have entered participant as a predictor variable. The results are very similar, with a main effect of block, target, rotation, and participant. Of course, it is not possible to assess an age group effect with this analysis method, or a landmark by block interaction, because each participant is in only one age group and experienced only one order of testing. There are two additional significant outcomes here: an Age Group × Target interaction and a Target × Rotation interaction. The first is driven by younger participants having larger average log-error for the targets farthest from the landmarks. The second is driven by longer rotations having a larger adverse effect on the same targets. On balance, these results support our main arguments in the text (Table A3).

Appendix D. Bootstrapping analysis

To better understand the potential effects of the 2D versus 3D landmarks, we also looked at overlapping heatmaps of the responses. This could give us some insight into what participants were doing differently in the two cases (i.e., whether there was some notable pattern of places they responded in

Table A3
ANOVA including participant as a variable.

	df	SS	F	η^2	p
Landmark type	1	0.912	1.507	.000	.220
Block	1	5.312	8.773	.003	.003
Target	9	134.988	24.771	.071	<.001
Rotation	7	95.279	22.479	.050	<.001
Participant	46	272.906	9.798	.144	<.001
Age group * Landmark Type	2	0.591	0.488	.000	.614
Age group * Block	2	3.083	2.546	.002	.079
Age group * Target	18	19.125	1.755	.010	.025
Age group * Rotation	14	7.028	0.829	.004	.638
Landmark type * Block	n/a	0.000	n/a	n/a	n/a
Landmark type * Target	9	4.362	0.800	.002	.616
Landmark type * Rotation	7	4.900	1.156	.003	.325
Block * Target	9	4.159	0.763	.002	.651
Block * Rotation	7	3.195	0.754	.002	.626
Target * Rotation	63	50.879	1.334	.027	.042
Error	2107	1275.781			
Total	2303	1899.778			

Note. Significant effects are in bold.

the 3D landmark case but not in the 2D landmark case). We separated the data into 20 different lists—1 for each target with 2D landmarks and then again for each target with 3D landmarks. (In other words, we collapsed over age, rotation, and testing block.) We smoothed the data in each list with a kernel density estimation method, using Scott's (1979) rule of thumb for the bandwidth at a resolution of 1 cm^2 per pixel for each target. We then looked at their differences across landmark types but within targets. This gives us a map of the relative local density of the responses in the two conditions. We then needed a way to separate these differences into ones that are statistically significant versus those that could plausibly just be noise. To test this, we developed a bootstrapping method.

To illustrate how this works, imagine a scenario where one would use a *t* test. There are two groups of data with 64 observations each, with a mean difference of 2 and each with a standard deviation of 1.5. The *t* distribution is useful here, but the test assumes that both are normally distributed. If both are highly non-normal, there is another method available. If the data from the two sets are pooled together and randomly sampled to form two groups over and over, the mean difference can be calculated for each remixing. After many remixes, the mean differences will have a certain apparent distribution. This distribution, which may or may not resemble a *t* distribution, will have extremes at both edges. The actual mean difference can be placed onto this distribution, and it is possible to infer whether that mean difference is extreme or not when the two groups actually have the same underlying distribution. In other words, one can estimate the likelihood of seeing the observed mean difference if the group labels are actually irrelevant and the true mean difference is zero. This method is generally not as powerful, but it is not laden with any assumptions about the distribution of the data. This is important here because there is no clear assumption about how differences in local density should be distributed.

We randomly sampled the two sets (within targets but across 2D vs. 3D) and recomputed the smoothed heatmaps, searched each for its largest difference, and repeated 1000 times. This gives us an empirical bootstrapping distribution of the kind of peak differences that are likely to occur by chance in these maps. This simulation lets us estimate a cutoff difference that is unlikely to occur in more than 5% of random arrangements (across 2D vs. 3D) for each target. We saw that the heatmaps of the actual data exceed this cutoff in only three places (bright white spots in Fig. A3), all in favor of higher 2D density and all near the target. This suggests, again, that there were no advantages for the 3D condition. Moreover, it does not suggest that any particular area was strongly distracting the 3D responses away from the target, so it is possible that they were not systematically incorrect but just simply more diffuse.
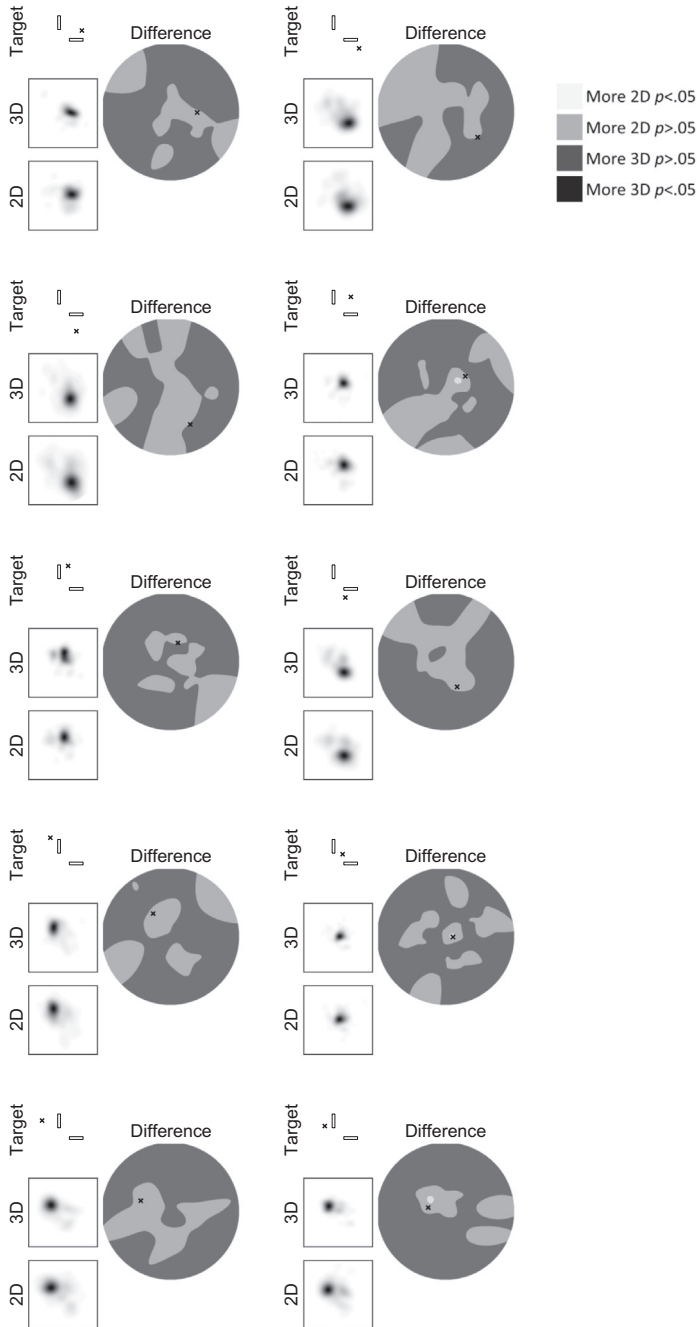
Fig. A3. For each of the 10 targets, there is a smoothed estimate of the density with 2D landmarks (lower left), 3D landmarks (middle left), their difference (right), and a display of the target relative to the landmarks (upper left). On the lower and middle left, darker indicates higher local density. Significant differences (very light gray or very dark gray) occur in only three places on the difference maps (second, fourth, and final maps in the right column), all in favor of higher local 2D density and all near the actual targets.

Table A4
Bayesian analysis results.

	P(incl)	P(incl|data)	Log(BF$_{Inclusion}$)
Age group	0.922	1	32.32
Target number	0.922	1	32.32
Rotation	0.922	1	32.32
Block	0.922	1	11.941
Landmark type × Block	0.428	1	11.803
Landmark type	0.922	1	9.687
Age group × Block	0.428	0.09	−2.027
Age group × Landmark type	0.428	0.015	−3.906
Age group × Target number	0.428	0.003	−5.408
Landmark type × Rotation	0.428	0.002	−5.881
Target number × Rotation	0.428	0.002	−5.943
Block × Target number	0.428	6.765e−4	−7.009
Landmark type × Target number	0.428	3.434e−4	−7.687
Block × Rotation	0.428	3.319e−4	−7.721
Age group × Rotation	0.428	5.576e−5	−9.506

Table A5
ANOVA including distance to the target.

	df	SS	F	η²	p
Age group	2	13.61	10.54	.007	<.001
Landmark type	1	2.63	4.08	.001	.044
Block	1	3.36	5.20	.002	.023
Target	9	28.66	4.93	.015	<.001
Rotation	7	10.63	2.35	.006	.021
Distance to view	1	11.03	17.10	.006	<.001
Age group * Landmark type	2	0.34	0.27	.000	.766
Age group * Block	2	2.36	1.83	.001	.161
Age group * Target	18	18.93	1.63	.010	.046
Age group * Rotation	14	6.18	0.68	.003	.792
Age group * Distance to view	2	0.66	0.51	.000	.600
Landmark type * Block	1	16.41	25.43	.009	<.001
Landmark type * Target	9	2.27	0.39	.001	.940
Landmark type * Rotation	7	5.15	1.14	.003	.335
Landmark type * Distance to view	1	2.12	3.29	.001	.070
Block * Target	9	4.35	0.75	.002	.665
Block * Rotation	7	3.39	0.75	.002	.629
Block * Distance to view	1	1.30	2.01	.001	.157
Target * Rotation	63	47.10	1.16	.025	.187
Target * Distance to view	9	12.61	2.17	.007	.021
Rotation * Distance to view	7	1.20	0.27	.001	.967
Error	2130	1374.66			
Total	2303	1899.78			

Note. Significant effects are in bold.

Appendix E. Bayesian version of the primary ANOVA

The Bayesian approach to data analysis is becoming more popular and more trusted in psychology, so we also present a version of our primary analysis in the Bayesian tradition. These figures were calculated in JASP 0.8.1.1 (https://jasp-stats.org/). In the right-most column, figures greater than 3 represent strong evidence that the effect exists and figures less than −3 represent strong evidence that it is not present. The results largely agree with the main analysis, with a main effect of rotation, target, age group, and block plus a Landmark Type × Block interaction. There is also a main effect of landmark type, suggesting that 2D performance was overall better than 3D performance. Results are inconclusive for a Block × Age Group interaction, and the rest of the effects are positively denied (Table A4).
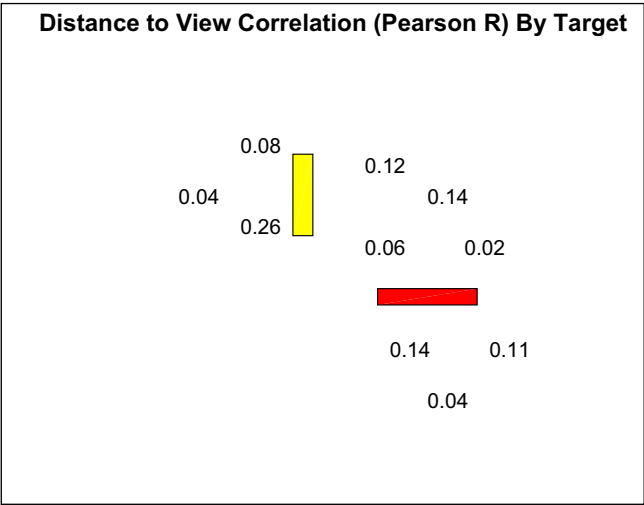
Fig. A4. Correlation between the distance to view and the log-error broken down by target location.

The appearance of the landmark type effect, as a side note, is an instance of an interesting but little-discussed advantage that Bayesian analysis can have. The Bayes factor over inclusion is calculated by estimating the posterior probability of all models that can be formed by combining the different main and interaction effects and then looking at the ratio between the prior probability of all models that have each effect to the total posterior probability of selecting a model that has the effect present. One of the outcomes of this is that it automatically "weights" the importance of other effects for analysis. The final posterior calculation included few models that feature interaction effects other than the Block × Landmark Type one. An ANOVA that includes just the main effects and the Block × Landmark Type interaction also finds the same landmark type main effect, $F(1, 2282) = 6.7094$, $p = .0097$. Removing the additional interactions has this effect because (a) it increases the error degrees of freedom and (b) parts of the sum of squares for the removed interactions are reassigned to the main effect. The Bayesian ANOVA does this kind of trimming online, automatically, without the loss of the ability to draw conclusions about the additional interactions. In other words, the main effect of landmark type could be a genuine one that only the Bayesian analysis could detect.

Appendix F. Distance to target

The planned analysis, presented in the main text, does not include the distance between the recall point and the correct target location as a covariate. This was planned as such because that distance is somewhat conflated with the target location; targets that are near the middle of the array are constrained in how far they can be away from the recall point when compared with targets on the exterior. However, because the two can be quantified independently on each trial, it seems plausible that needing to point farther away would lead to higher error, and the reader may be interested in any effects it may have. We ran an additional unplanned 3 (Age Group) × 2 (Landmark Type) × 2 (Testing Block) × 10 (Target) × 8 (Rotation) × Continuous (distance from target to recall point) ANOVA. The results are in Table A5.

Under this analysis, all main effects are significant, as are the Landmark Type × Testing Block, Age Group × Target, and Target × Distance to View interactions. Comparing this with the main analysis, the biggest change is that 2D landmarks led to significantly smaller errors than 3D ones. As with other alternative analyses, there was also an Age Group × Target interaction, where the youngest children had the greater errors when faced with the most difficult targets (those farthest away from the landmarks). However, note that this is a move from $p = .054$ to $p = .046$, so it does move the p value over
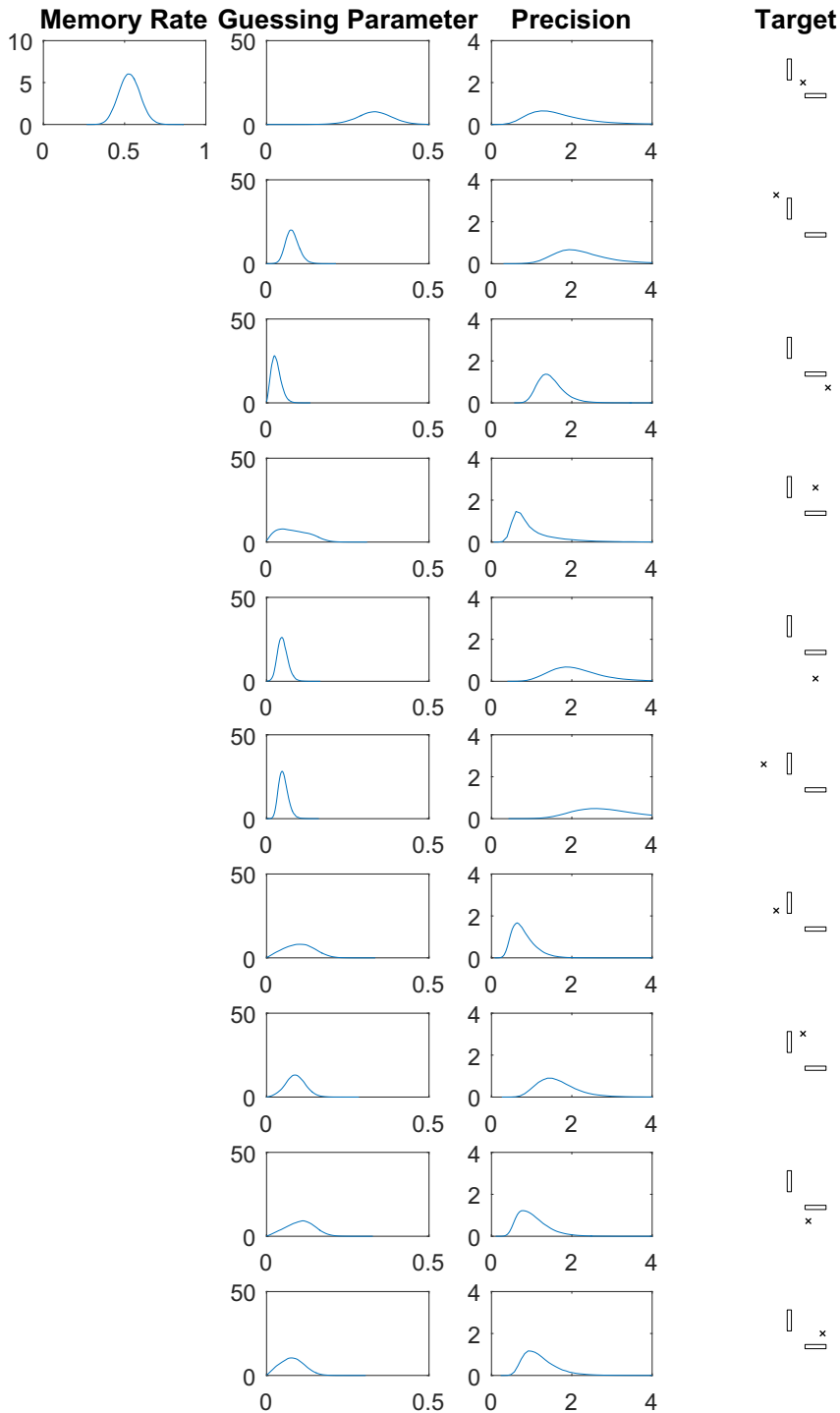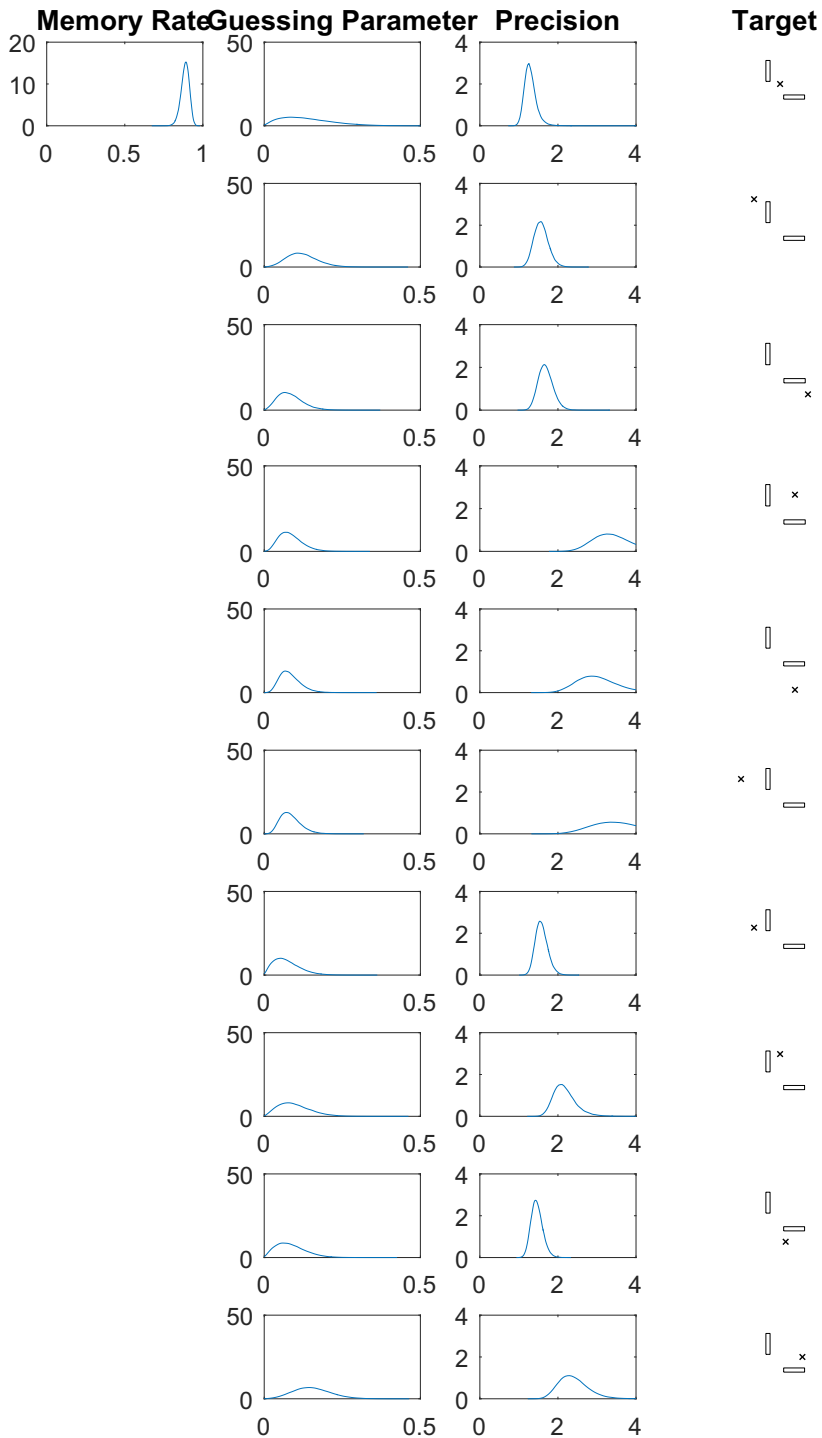
Fig. A5. Model results for participants aged 4.5–5.5 years.
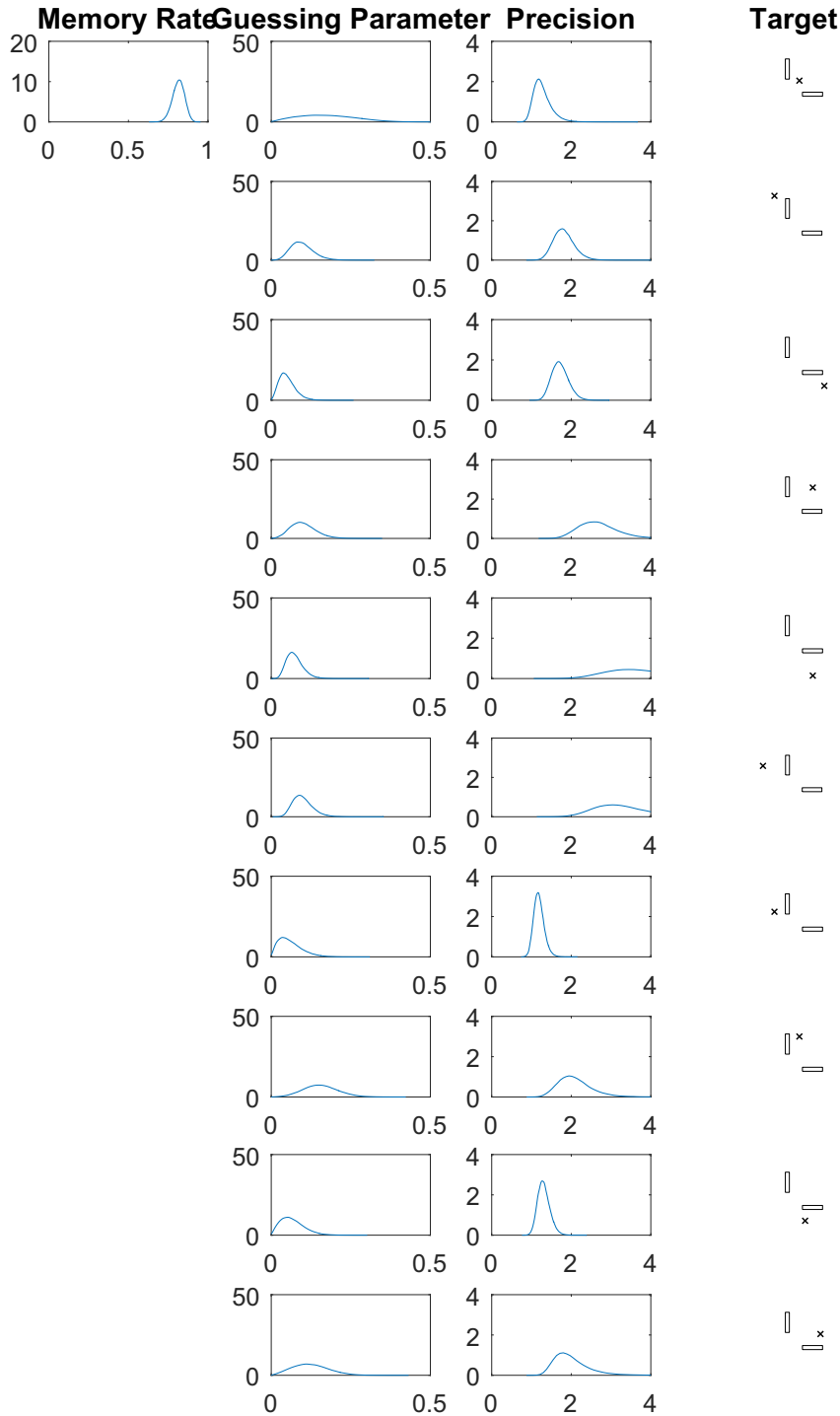
Fig. A6. Model results for participants aged 5.5–6.5 years.

Fig. A7. Model results for participants aged 6.5–8.5 years.

the significance threshold, but only by changing it by less than 1%. Finally, there was also an interaction between target and distance to view, with the target directly in the middle and the two farthest targets showing the least sensitivity to the distance to view (Fig. A4).

Appendix G. Modeling results in separate age groups

The modeling results in the main text used the full age range from 4.5 to 8.5 years. This leaves open the question of whether and how the results might change across smaller age ranges. In this appendix, we give the results obtained when running the model on the three age groups: 4.5–5.5 years, 5.5–6.5 years, and 6.5–8.5 years (see Figs. A5–A7).

As one would expect, the memory rate trends upward as age increases. This means that in the youngest group, guessing parameters have smaller credible intervals and precision parameters have larger credible intervals—and vice versa for the oldest group. It is also true that the overall size of credible intervals has generally increased given that fewer data are available for each analysis. However, beyond this, results look broadly similar. For all three age groups, the target in the middle has a relatively high guessing parameter and a precision that is not especially high. If there is any noteworthy change at all, it is the fact that precision was lower for the fourth target down in Fig. A5 for the youngest children, indicating that the target that was equidistant from the two landmarks but not directly in the middle was more difficult for the youngest children.

Appendix H. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jecp.2017.12.009.

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