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Development of the Ability to Integrate Egocentric and Allocentric Coordinates in a Blindfolded Navigation Task

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ABSTRACT

Spatial orientation during locomotion is a fundamental daily function that requires building mental representations of the surrounding environment. Spatial representations are based on egocentric (self-based) and allocentric (world-based) frames of reference. Representing space according to the allocentric perspective is not fully developed in childhood. This study investigated spatial representation skills in 41 Italian children aged 6 to 11 years old (18F; mean age ± SD: 9 ± 1.58) using a spatial navigation task with no visual cues available. The task was carried out in a local school (Genoa, Italy). The children were blindfolded and guided along a path. The room they walked through was divided into four quadrants, each signaled by an animal-shaped landmark. Before each trial, they observed the landmarks from the starting position. At the end of the path, they were asked to localize all the landmarks. Children were required to represent the relationship among the four landmarks regardless of their position in the room to accomplish the task. The results showed that children had higher accuracy when they were in the same quadrant as the landmark to be indicated across all ages. Interestingly, accuracy increased with age when the child's position was different from the position of the target landmark (incongruent condition). Additionally, greater path angle amplitude led to lower accuracy across conditions. These findings provide new insights into human spatial development: the ability to represent the environment with an allocentric perspective, based only on self-motion information and previously learned visual landmarks, continues to develop during childhood.

Introduction

Children's spatial representation and navigation abilities undergo significant development throughout childhood and are not fully mature until adolescence (Newcombe, 2019; Tansan et al., 2022). To build an effective representation of space, there is a need to combine egocentric and allocentric perspectives. Egocentric perspective relies on spatial cues from one's own position, while allocentric perspective encodes metric relations among objects regardless of self-location. When humans form spatial representations of the surroundings, they collect information coming from different sensory modalities, internal (related to the body), and external (related to the environment). Self-motion cues (vestibular and proprioceptive) are relevant to updating one's own movements when external references are not available or reliable (Loomis, 1999). During navigation, landmarks, i.e., the fixed external

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points of reference, are crucial to help recognize a place and their processing dynamically interacts with internal motion cues (Zhang & Mou, 2017). In fact, landmarks aid the combination of egocentric and allocentric perspectives because they provide the traveler with information on both the spatial distance and the relation between the traveler and the landmark and among landmarks themselves (Chan et al., 2012). It follows that correct landmark localization may require both accurate path integration (updating one's own position) and memory of the landmark configuration (for a review: Lee, 2023). Investigating how the memory of landmarks in space and self-motion-related cues are combined during childhood may help understand the developmental trajectory of spatial navigation abilities.

In a spatial navigation task, we can postulate four possible performance patterns depending on accuracy in path integration and landmark memory gained before moving (i.e., encoding). In detail:

(1) Accurate path integration and landmark memory: Children should successfully localize the landmarks regardless of where they land after moving, showing high accuracy overall.
(2) Accurate path integration, poor landmark memory: Good performance is expected only when the landmark is in the same egocentric area as at encoding. Accuracy should drop when the spatial congruence condition is not met.
(3) Poor path integration, accurate landmark memory: Children may rely on an approximate sense of the landmark layout, leading to moderate accuracy, regardless of body position relative to landmarks.
(4) Poor path integration and poor landmark memory: Performance should be generally low, possibly influenced more by body movement (e.g., direction turned) than spatial layout, with no reliable effect of body-landmark spatial congruence.

Past research shows young children process spatial information using a rudimentary allocentric perspective. Literature indicates that 4-year-olds can accurately locate objects after being disoriented (Huttenlocher & Vasilyeva, 2003) or after walking to a new observation point without vision (Rieser & Rider, 1991). This suggests that they are able to consider the environmental features as a whole, rather than remaining anchored to the initial body-object relationship. Evidence supports the use of allocentric reasoning already by 4.5-year-old children to recall targets (Negen et al., 2018) and by 5-year-olds when the use of allocentric information is imposed to accomplish a virtual spatial navigation task (Bullens et al., 2010). In contrast, more recent research involving a more open virtual environment, shows that 9–10-year-old children outperform 5-to-8-year-old peers in processing proximal landmarks, thus indicating that the ability to process allocentric information may develop later in childhood (van Hoogmoed et al., 2022; for a review, see Tansan et al., 2022). This literature does not clarify how different sensory inputs (i.e., self-motion and visual cues) contribute to forming spatial representations of the environment, combining egocentric and allocentric perspectives. Moreover, the developmental trajectory of these abilities is not clear.

The aim of this study was to explore the ability to encode space in egocentric and allocentric perspectives during development. Since the processes of sensory cross-calibration fundamental to developing functional multisensory perception occur during the first scholar years (Gori, 2015; Gori et al., 2008, 2012) and complex navigation skills are acquired in the same period (Overman et al., 1996), we recruited children from 6 to 11 years old from a local school (Genoa, Italy). We asked, how does development influence the integration of egocentric and allocentric information in the use of spatial cognitive maps? We expect that for the youngest children, the allocentric encoding would not be completely developed. As a consequence, they would have more difficulties in correctly indicating the position of landmarks that were different relative to participants' landing position after blindfolded spatial navigation, thus indicating that the integration of egocentric and allocentric coordinates in the construction of cognitive maps improves during development.

Method

The study was performed in accordance with the Declaration of Helsinki (2013). The procedure was approved by the ethics committee of the local health service (Ethical Committee, ASL 3, Genoa, Italy). Forty-one children (age range: 6–11 years old) from a school in Genoa participated in the study. Their parents gave written informed consent. Children were gathered by their classrooms, forming three groups: 6–7 y.o. ($n = 11$; four females), 8–9 y.o. ($n = 19$; 10 females) and 10–11 y.o. ($n = 11$; four females). The data reported in the present study were acquired from the same sample as those participating in a previously published study (Cuturi et al., 2017).

The experiment was carried out in a classroom where furniture was removed for experimental purposes. Children stood on the same starting point on each trial (see Start in Figure 1). The experimenter guided the children along a two-segment path, the first one 225 cm long and the second one 120 cm long (an example of the path can be observed in the central panel of Figure 1, in green). To ensure they could not see their steps and the floor, we provided participants with a blindfold and a customized silicone bib.

The turning angle between path segments varied trial-by-trial, ranging from ± 50° to ± 130° in 20° steps (negative values indicate left turns, positive values indicate right turns). Each angle level was repeated twice, resulting in 20 "journeys" from the starting point to the endpoint per child. We pseudo-randomized the order of angles using the following

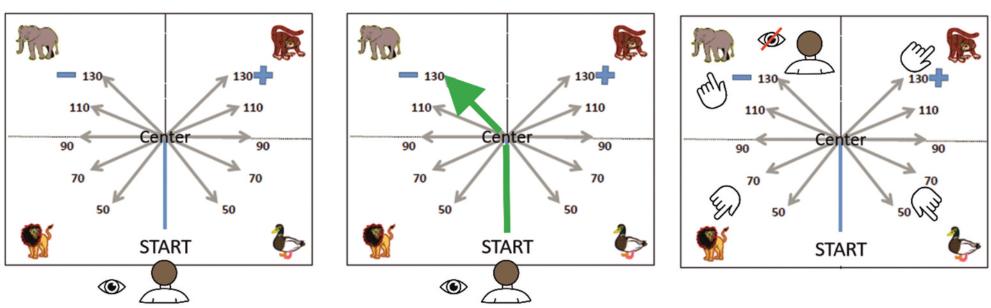

Figure 1. Sketch representation of the experimental procedure. In the left panel, the child is at the starting position facing landmarks, without any visual cover in order to observe and memorize animal-shaped landmarks' positions. In the central panel, the child is provided with the silicone bib (no visual cues available) and follow the two-segment path (the arrow colored in green) and land on the elephant landmark quadrant. In the right panel, the child attempts to indicate with the index finger the locations of all landmarks, again with no visual cues available.

sequence (applied to both left and right turns): ±110°, ±70°, ±130°, ±90°, ±110°, ±50°, ±70°, ±130°, ±50°, ±90°. Left-turn and right-turn blocks were conducted separately. The walking space was divided into four quadrants signaled by four portraits of animals (an elephant, a lion, a monkey, and a duck).

Before each trial, children were told they would walk blindfolded and then point to the four animal-shaped landmarks (80 responses each). We first encouraged children to look and memorize the position of the animals before starting each trial. Once participants reached the end of the two-segment path, we asked them to point with their index finger toward all animal-shaped landmarks. Responses were taken as indicated quadrant. After the answer, children were guided to the original starting position. On the way back to the next trial, the experimenter randomly moved the children (who kept their eyes closed) around the room to disrupt as much self-motion information as possible.

Data analysis

We coded the correct responses when children correctly indicated the quadrant of the requested landmark and computed the proportion of correct responses for each angle and for each repetition of stimuli. We separated the conditions in which the landing position of children and the landmark target location were the same (congruent condition) and conditions in which they were different (incongruent condition). An example of a congruent condition was when the child landed on the elephant quadrant and was asked to localize the elephant landmark (see Figure 2 on the left, aqua green upper left quadrant). An example of an incongruent condition was when the child landed on the elephant quadrant and was asked to localize the monkey, the duck, or the lion landmarks (see Figure 2, reddish quadrants). Considering the congruence definition, we excluded from this analysis turning points that lead to ± 90°, because in those cases, congruence between landing position and

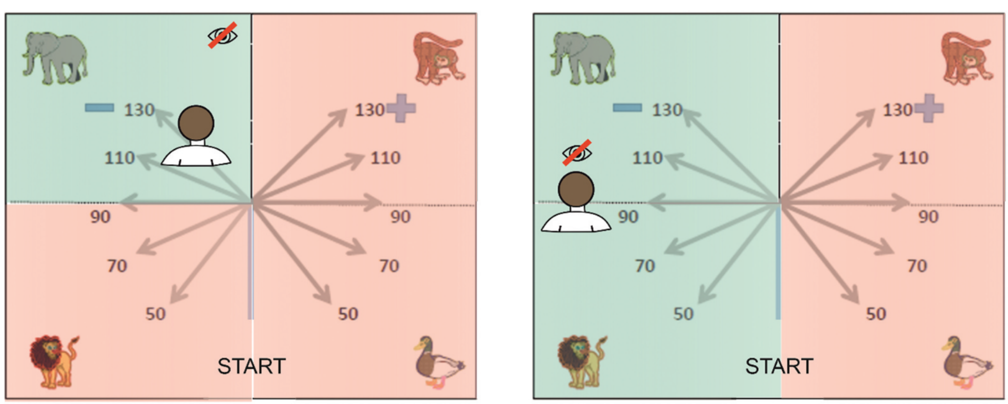

Figure 2. In the left panel, the child landed on the elephant quadrant. In this trial, the child's position is congruent with the elephant's one (in aqua green) and incongruent with the one of the lion, the monkey and the duck (reddish quadrants). In the right panel, the child landed on −90° landing point. In this case, the child's position is congruent with both the elephant and lion locations (in aqua green), while it is incongruent with the monkey and the duck locations (reddish quadrants).

landmark target location was not clearly definable. This way, we obtained 64 responses for each condition for each child (8 angles * 2 repetitions * 4 landmarks).

We used a mixed-effects logistic regression analysis to model the probability of a correct response as a function of congruence as previously defined, age, the interaction between age and congruence, sex, amplitude of the angle (absolute values), side of the room (left-turn vs right-turn) and order of trial to test for potential learning effect:

Response ~ Congruence * age + abs(angle) + side + sex + trial + (1 | subj)

We chose this model because of the binary correct/incorrect nature of the dependent variable. Statistical analyses were performed in RStudio using *glmer* function from *lme4* package (Bates et al., 2014) and *emmeans* from *emmeans* library to explore pairwise comparisons. To reduce multicollinearity among the interaction terms (Congruence and age), we centered the continuous variable age to facilitate the interpretation of the intercept and interaction terms. For the categorical predictor Congruence, we used effect coding (−0.5 for incongruent, +0.5 for congruent) to ensure that the main effect of age reflects the average across both congruent and incongruent trials, rather than being anchored to a specific condition (Jaccard & Turrisi, 2003). To further test for multicollinearity, we computed variance inflation factors (VIFs) and they were found to be around 1.35 and less than the conservative threshold of 2, thus suggesting that multicollinearity was not a major issue in our model.

We performed a similar analysis for responses to ± 90° turning points, redefining Congruence as the equality between the side of the room of the landing position and the side of the room of the target landmark:

Response ~ Side_congruence * age + side + sex + trial + (1 | subj)

In this case, landing on −90° would be congruent with elephant and lion landmarks and incongruent with monkey and duck landmarks (Figure 2, right panel).

Results

The results of the generalized linear mixed model show that the Congruence predictor seems to have a significant and positive effect on the likelihood of correct responses (Estimate = 2.75, $p < 0.001$). We also observe a significant influence of the absolute amplitude of angles. In particular, Tukey-adjusted post-hoc tests show that, regardless of congruence, children had higher accuracy in identifying the target landmarks when turning the 130° angle relative to 50° (Estimate = −0.38, $p = 0.02$), 70° (Estimate = −0.41, $p = 0.01$) and 110° (Estimate = −0.53, $p = 0.001$). Sex did not show any significant effect (Estimate = 0.18, $p = 0.32$). Interestingly, we found a significantly better performance for right-turn trials than for left-turn trials (Estimate = −0.27, $p = 0.002$). Finally, a significant decrease in accuracy was found as the trials progressed (Estimate = −0.01, $p = 0.005$).

The interaction between Congruence and age was significant, with a negative coefficient (Estimate = −0.24, $p = 0.04$; see Figure 3). Specifically, if we take Congruent and Incongruent conditions separately (applying a generalized linear model on the probability of correct responses with age as a continuous predictor, maintaining angle, sex and trial as other predictors), age has a significant positive effect on the probability of correct responses in the incongruent condition (Estimate = 0.13, $p < 0.01$), while it has no effect in the congruent condition (Estimate: −0.10, $p = 0.38$). Thus, in congruent trials, all ages showed ceiling performance, while in incongruent trials, accuracy improved with age. This model appeared to fit our data well according to the AIC of 2845.2 relative to the intercept model (baseline model containing no fixed effects, and only the subjects as random effects resulted in AIC = 3265.8; $\chi^2(9) = 438.63$, $p < 0.001$). Nonetheless, the model explained about 30% of the total variance in the data (Conditional $R^2 = 0.351$) with a small contribution of the fixed effects (Marginal $R^2 = 0.301$). The difference between conditional and marginal R^2 indicates how much variance is present on the subject level and captured by the random effects in our model.

Similar results were obtained with the analysis on angles ± 90° (Figure 4). Results from the generalized linear mixed model suggested that the Congruence predictor showed a significant negative effect on the probability of correct responses (Estimate: −2.09,

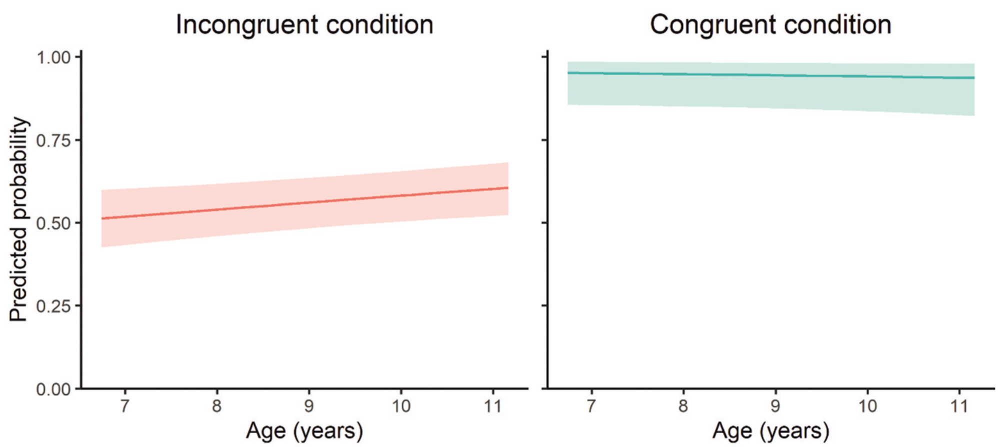

Figure 3. Representation of the predicted probability of correct responses in incongruent vs congruent condition defined for ±130°, 110°, 70°, 50° turning angles in function of age.

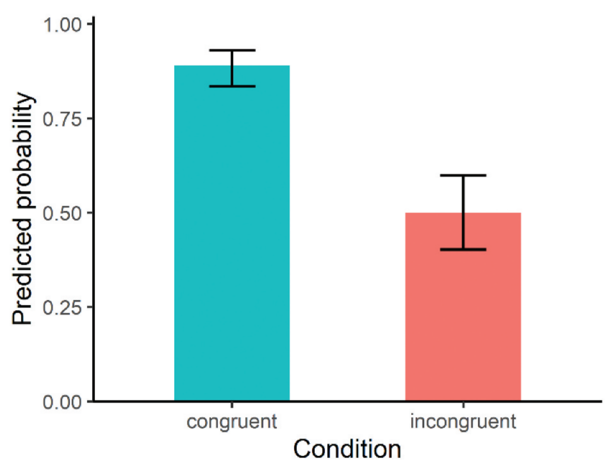

Figure 4. Representation of the predicted probability of correct responses in congruent vs incongruent condition defined for ±90° turning angles.

$p < 0.001$). Neither the age predictor (Estimate: 0.12, $p = 0.3$) nor the interaction between Congruence and age (Estimate = 0.0003, $p = 0.99$) showed a significant effect on the probability of correct responses. Again, sex was found not to have a significant effect (Estimate = 0.05, $p = 0.85$). This time, there was no difference in accuracy for the side of the room (Estimate = 0.01, $p = 0.92$). This model seems to fit our data well according to the AIC of 698.2 relative to the intercept model (baseline model containing no fixed effects, and only the subjects as random effects resulted in AIC = 808.7; $\chi^2(6) = 122.5$, $p < 0.001$). The generalized linear mixed model on ± 90° trials suggests that Congruence, this time defined as congruence between the room side of the landing and the position of the target landmark, may be the primary explanatory factor for our data, with any influence of age on children's performance. This model including the side of the room congruence as predictor explains about 30% of the total variance (Conditional $R^2 = 0.303$) with a small contribution of the fixed effects (Marginal $R^2 = 0.243$).

Globally, our findings suggest that the generalized linear mixed-effects models partially explained children's spatial behavior, failing to explain the majority of the variance. Other sources of information that we did not investigate may likely explain children's navigational abilities more comprehensively.

Discussion

In the present study, we investigated the integration of egocentric and allocentric representation abilities in Italian children aged 6–11 years, using a blindfolded spatial navigation task. Performance was measured as accuracy in locating four animal-shaped landmarks in each corner of the experimental room, relying solely on spatial information from self-motion. We aimed to study the developmental trajectory of allocentric representation abilities without visual cues. We observed an interaction between age and the congruence condition, showing that younger children had more difficulties in building an allocentric representation of the room based on landmarks location if compared with older children. Besides, even older children showed non-optimal performance in Incongruent conditions. Considering literature about adults' ability in allocentric spatial tasks (e.g., Fernandez-Baizan et al., 2021) and self-orientation without vision (Frissen et al., 2011), this result may suggest that the involved spatial cognitive functions could keep developing even after 11 years old, but further research needs to address this late developmental trajectory. No sex differences were found, but performance was better when turning 130° or to the right, and accuracy declined over trials.

In our task, when the navigational path led participants to a position incongruent with the target landmark, all children showed immature ability of building an efficient allocentric representation of the room. Previous literature on spatial processing during childhood showed that children develop spatial abilities starting from an egocentric perspective and learn only later how to use geometric and landmark-based signals coming from the environment (Newcombe, 2019; Tansan et al., 2022). Still, evidence shows that even during the first year of life, infants are able to use an allocentric framework to code space (Lew et al., 2000; Newcombe et al., 1998), at least in a rudimentary way. Indeed, they begin to show the ability to rely on landmarks starting from the age of 12–21 months (Lew et al., 2000; Newcombe et al., 1998). Children progressively learn to spatially represent the relations between distal landmarks throughout childhood (Nardini et al., 2009; Overman et al., 1996; Rieser & Rider, 1991; van Hoogmoed et al., 2022), usually reaching an adult-like behavior around 10 years old (Bullens et al., 2010).

Our results partially contrast with previous research, showing that children up to 11 years old did not reach optimal allocentric reasoning. Remarkably, the difficulty of our task consisted of removing visual information when children changed their perspective from the start position to the landing one. In this way, and different from previous studies, children were required to perform two tasks at the same time. First, they had to keep in memory the spatial layout of the animal-shaped landmarks, which they observed at the beginning of the trial; second, they had to update their position in the room and build the spatial relationship between their new position, adopting a novel perspective, and the configuration of landmarks. Spatial orientation while walking without visual cues implies the ability to keep updated complex geometric changes between the navigator and environmental objects (Rieser & Rider, 1991). In other words, our task required to efficiently integrate egocentric and allocentric frames of reference, which is still not mature until late (Nardini et al., 2008).

In the congruent conditions, participants showed a near-ceiling performance in updating their position without visual self-motion information, thus relying solely on vestibular and proprioceptive signals. This condition has been interpreted as the more egocentric component of the present task, because identifying the landmark corresponding to the landing target location requires correctly updating the body position in the room, with no need of remembering the allocentric configuration of the other landmarks. This finding is actually in line with previous studies that show the development of path integration abilities during 6–11 y.o. age range (Cuturi et al., 2021; Smith et al., 2013). These results allow us to rule out that any errors in allocentric reasoning can be explained by a spatial memory deficit: indeed, if children had simply forgotten the position of all animal-shaped landmarks in the room, they would have produced several errors in recollecting the landmark available in the quadrant congruent with their landing position. In our case, we observed that they did not fail to recollect the congruent animal, but they specifically failed to link their updated position with the spatial relationship among the four landmarks. This finding is in line with previous results from Rieser and Rider (1991). Indeed, these authors asked a group of adults and a group of 4-years-old children to localize three to five targets after walking without vision, observing above-chance performance for both adult and children groups, with better performance in adults than children. However, the experimenters asked participants to study the positions of each target, requiring them to remember the location of each of them without focusing on the spatial relationship among them. Like theirs, the children in our study (even the youngest) succeeded in localizing one target but failed in reconstructing the complex spatial layout of multiple landmarks.

In light of our results from the congruent and incongruent conditions, we propose that the strategy children use to navigate blindfolded tasks primarily relies on an egocentric perspective (as hypothesized in Bullet (2) in the Introduction section). This suggests a lack of integration between path integration and landmark memory. Although we did not directly assess the children's understanding of landmark configuration, nor did we separately evaluate their ability to recall landmark locations without self-motion cues, the comparison between congruent and incongruent conditions provides valuable insights. Specifically, when the spatial correspondence between the child's body and the landmark location was intact, children were able to combine the two types of information effectively. However, introducing a spatial mismatch disrupted this ability. Future studies could directly investigate landmark memory and navigation to better disentangle these processes.

Another interesting result is the effect of angle amplitude on performance. It needs to be noted that the greater amplitude in our setup (the angle indicated by 130°) actually corresponds to the smallest turn that the child had to do, guided by the experimenter. Indeed, turning the angle 50° implies to walk the supplementary angle amplitude starting from 0°, that is 130°. Conversely, turning the angle 130° implies deviating from straight-forward 0° direction only by 50° (Figure 5). As previous literature reported (Cuturi et al., 2021), navigators of all ages produce more errors as the amplitude of yaw rotations increases. This is because path integration process leads to rapid accumulation of errors when in the absence of external cues, such as external landmarks (Etienne & Jeffery, 2004). This means that greater yaw rotation causes stronger disorientation (Cuturi et al., 2021).

Interestingly, this self-motion-based information substantially influenced the ability to identify the correct location of the external landmarks. The higher the disorientation in terms of proprioceptive and vestibular cues, the lower was the ability to successfully recall the location of the external landmarks. While we noted good performance in the congruent condition for all ages, it is possible that a great disorientation leads to poorer ability to use the self-motion information to process the allocentric configuration of the environment when there is no correspondence between body position and target position. However, we could not evaluate the direct interaction between angle and congruence due to poor data sparsity. Future studies may directly address this scientific question.

Another noteworthy finding concerns the effect of trial progression. Specifically, children's performance declined over the course of the session, likely due to fatigue or reduced attention over time. Importantly, the pseudo-randomized order of turning angles minimized the potential for learning effects that might have otherwise improved accuracy across trials.

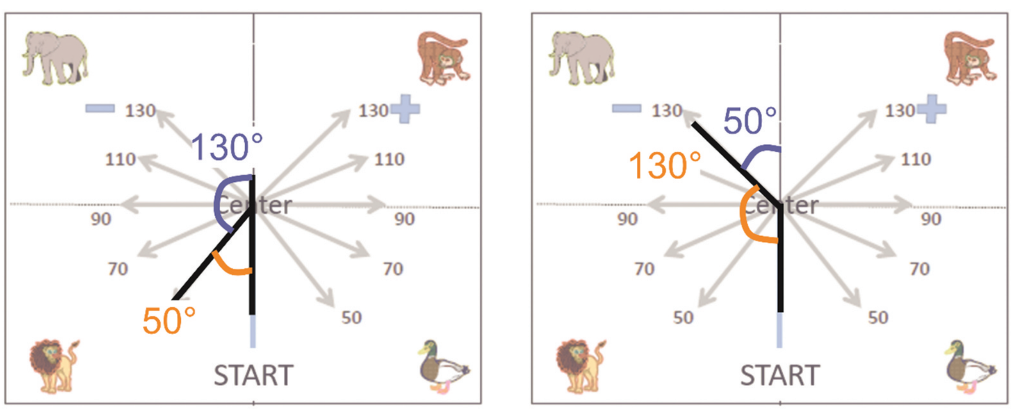

Figure 5. Illustration of two example turning angles. In the left panel, the child is guided along a 50° path (orange), but must physically turn 130° (dark blue) to reach the correct lion quadrant. In contrast, in the right panel, the child is guided along a 130° path (orange), yet only needs to make a 50° turn (dark blue) with their body to reach the elephant quadrant target.

The presence of generally better performance in response to right turns compared to left for ± 50°, ±70°, ±110° and ± 130° angles is somewhat unexpected. Previous findings showed that the ability to categorize left and right sides, both linguistically and conceptually, influences overall spatial abilities (Hermer-Vazquez et al., 2001) and especially egocentric spatial navigation (van Hoogmoed et al., 2022), as this ability develops with age. Interestingly, research on adults performing a walking angle task showed systematic biases that correlate across sides, corresponding to a deviation from straight ahead (Jetzschke et al., 2016). Although such correlation has not been found in children (Cuturi et al., 2017), it may be considered to be explored in further investigation to provide a better understanding of the observed asymmetry.

Notably, sex-related differences were not found. Although generally literature reports small to moderate sex differences in spatial navigation abilities (e.g., van Hoogmoed et al., 2022), with males outperforming females, a meta-analysis showed that these differences are substantially smaller or absent in participants younger than 13 years old than in older groups (Nazareth et al., 2019), as found, for example, in (Fernandez-Baizan et al., 2019). This may suggest that spatial differences may rely on habits or spatial tasks in daily life more than on intrinsic spatial processing and functioning.

This study should be evaluated in light of two main limitations. First, we did not compare children's performance with adults'. We made this choice because of the simplified experimental procedure we implemented for children. Indeed, it can be speculated that adults would have not had any difficulties in remembering the spatial relationship among the small number of landmarks used and in collecting self-motion information to update their position in the room, as shown in Rieser and Rider (1991). Second, we found a significant interaction between age groups and condition of congruence, but the variance explained by our linear model was not large. This means that other factors that we did not include in our model may add to the investigation of the observed behavior. Future studies may be addressed to investigate the potential influence of individual experiences with spatial encoding and allocentric reasoning: similar to the adult population, by the age of 12 years old, differences in cognitive mapping tasks requiring the integration of multiple viewpoints into environmental space can be observed in children (Nazareth et al., 2018). In addition, since we did not observe adult-like performance even in the tested older children, future studies may be aimed at involving pre-adolescent and adolescents to find the crucial turning point between childhood and adulthood in building an efficient allocentric perspective. Even though treating age as a continuous predictor helps investigate the linear developmental trajectory of the interested spatial processes, a future optimal setup would also balance sample size for each school class.

Overall, while the present results reflect the specific conditions under which our study was conducted, our findings support a slow development of the representation of allocentric space, resulting in a progressive improvement in retaining elaborate representations of the environment while navigating without the concomitant visual information coming from self-motion.

Acknowledgments

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Data availability statement

All raw data have been made publicly available on the Zenodo repository (10.5281/zenodo.15547231). Data were analyzed using R, version 4.3.0 (R Core Team, 2023). This study was not preregistered.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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