

Development of different spatial frames of reference for orientation in small-scale environments

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Abstract

Background: Previous studies show that there is a developmental transition in the frames of reference children use to orientate from a body-centered to an allocentric strategy. However, there is no agreement concerning the age at which they begin to integrate and flexibly use both strategies in small-scale environments. **Method:** 6-10-year-old children and adults were trained to locate a hidden object in an arm-maze placed within a small-scale model, which maintained stable relationships with the frames of reference provided by the experimental room and by the subject (Experiment 1), and in a situation of inconsistency between the frame provided by the small-scale model and the other two (Experiment 2). **Results:** When the frames of reference provided by the room and by the subject conflict with that of the manipulative space, the performance deteriorates compared to the situation when multiple frames of reference can be used cooperatively to locate the goal. The flexible use of the information provided by the model (i.e., the cues surrounding the maze and the geometrical features) emerged at 10 years. **Conclusions:** Through development, children acquire new spatial abilities and increasing flexibility in the conjoint use of egocentric and allocentric frames of reference in small-scale environments.

Keywords: Spatial orientation, development, egocentric and allocentric frames of reference, small-scale environments, disorientation.

Resumen

Desarrollo de diferentes marcos de referencia espacial para la orientación en entornos a pequeña escala. Antecedentes: estudios previos muestran una transición durante el desarrollo en las estrategias que los niños utilizan para orientarse, aunque no hay consenso en la edad de inicio para emplear conjuntamente estrategias allocéntricas y egocéntricas en entornos a pequeña escala. **Método:** niños de 6-10 años y adultos fueron entrenados para encontrar un objeto escondido en un laberinto radial ubicado en una maqueta que mantiene una relación constante con los marcos de referencia proporcionados por la habitación experimental y por el participante (experimento 1), y en una situación de inconsistencia entre el marco de referencia del entorno a pequeña escala y los de la habitación y el sujeto (experimento 2). **Resultados:** cuando los marcos de referencia de la habitación y el sujeto entran en conflicto con el del espacio manipulativo, la ejecución empeora respecto a una situación en que múltiples marcos de referencia cooperan para localizar la meta. Desde los 10 años los niños usan la información del espacio manipulativo, tanto las claves que rodean al laberinto como la geometría de dicho entorno. **Conclusiones:** durante el desarrollo los niños adquieren nuevas habilidades espaciales y mayor flexibilidad en el uso conjunto de marcos de referencia egocéntricos y allocéntricos en entornos a pequeña escala.

Palabras clave: orientación espacial, desarrollo, marcos de referencia egocéntricos y allocéntricos, desorientación, entornos a pequeña escala.

Children show progressively more complex and flexible spatial capacities to navigate in their environment (Newcombe & Huttenlocher, 2003). Several studies suggest that there is a developmental transition in the frames of reference that children use to represent a spatial location, from an initial egocentric or body-centered frame of reference to an allocentric one. In an allocentric frame of reference, places are defined on the basis of their relationships with the configuration of environmental cues and independently of the observer's actual position (Lehning, Leplow, Ekroll, Herzog, Mehdorn, & Ferstl, 2003; Piaget & Inhelder, 1967).

In regard to the reorientation capabilities that children show when they are disoriented, many authors have proposed that the geometry of the environment can be used to reorient at very early ages. However, there is a lack of agreement concerning the age at which children begin to integrate this information with landmark features (Cheng & Newcombe, 2005). The fact that landmarks are perceived as stable features of the environment, that the size of the experimental environment permits the immersion of the subject and that the procedure employed for disorientation consists of the movement of the observer rather than the space all facilitate the use of cues for reorientation (Gouteaux, Vauclair, & Thinus-Blanc, 2001; Hupbach & Nadel, 2005; Lourenco & Huttenlocher, 2006; Nardini, Burgess, Breckenridge, & Atkinson, 2006). However, works that analyze the development of the capacity to learn a location in the manipulatory space using small-scale models of the environment as reference, as well as the possible interactions of this frame of reference with other egocentric or allocentric (i.e., centered on the experimental room) strategies, remain scarce.

The present work aimed to study the development of spatial learning abilities in a small-scale environment, which enables to analyze, under highly controlled conditions, the use of different strategies and frames of reference for orientation. Specifically, we analyzed the spatial strategies used by 6-10-year-old children and adults to locate a goal place in a radial-arm maze situated in a tabletop model of a room. The following two conditions were analyzed: a situation of consistency among the frames of reference provided by the model, the experimental room, and the position of the participant (Experiment 1) and a situation in which these frames of reference are made inconsistent by rotating the model (Experiment 2).

EXPERIMENT 1:

ORIENTATION STRATEGIES OF 6- AND 10-YEAR-OLD CHILDREN IN A MANIPULATORY SMALL-SCALE ENVIRONMENT

Method

Participants

Participants were 48 children, ages 6 and 10 years ($n = 24$ each). An equal number of boys and girls participated. None of the children had special education needs or neurological disorders that could potentially affect their cognitive performance. This study was conducted in accordance with the European Directive 2001/20EC and Helsinki Declaration for biomedical research involving humans and with the approval of the Bioethical Committee of the University of Seville (2008/12/02).

Instruments

The experimental apparatus consisted of a small-scale tabletop model of a sitting-room (Figure 1A). This manipulatory space included a four-arm maze (each arm was $30 \times 3 \times 2$ cm) surrounded by an array of five small pieces of furniture (peripheral cues) on a white board (79×59 cm). At the end of each arm, except for the start arm, there was a small inverted container (3.5 cm diameter) that could hide a reinforcer (a play dough ball). The goal (reinforced-container) was signaled by a guidance-cue (a 2.5 cm diameter \times 4 cm high flag) that was placed 1 cm behind it.

Procedure

Pre-training. Prior to the beginning of the experiment and in a room other than the experimental room, the participants were individually trained to locate the reinforcer hidden beneath one of the containers. During this phase, the location of the reinforcer varied pseudo-randomly in the different arms. The maze was placed in the center of the board; the guidance and the peripheral cues were excluded during this phase. The children sat in a chair in front of the board and the examiner. Each trial was preceded by a 15-s period, during which the child's eyes were covered. During the trial, the examiner provided the following instruction: "Search for the reinforcer by moving this token from its start position up to the end of the arm where the container that you think hides the reinforcer is located". Pre-training ended when the participants learned to move the token (2-cm diameter) along the maze-arms and search for the reinforcer beneath the containers.

Training. Training was conducted in an irregular-shaped room ($4.9 \times 3.4 \times 3.6$ m long and 2.5 m high) with many visual cues. The children were trained in a mixed, place-guidance procedure (Figure 1A). The goal was placed in a constant position (arm A, dotted circle in Figure 1A) relative to the cues provided by the experimental room and the small-scale model (place-learning) and was signaled by a small flag (guidance-cue). The small-scale model remained in a constant position relative to the children. The children (signaled by S in Figure 1) sat in front of the board and the examiner. Three start positions were used (arms B, C, D) in a pseudo-random order. To exclude the use of intramaze cues, the four-arm maze was rotated between trials. Prior to each trial, the participants covered their eyes for 15 s. A choice was recorded each time the children moved the token along a maze-arm and raised the container that was placed at the end. A correct choice was recorded when the first choice was the reinforced arm. A correction procedure was used such that the children were permitted to search for the reinforcer until they succeeded. The acquisition criterion consisted of 12 correct trials out of 15 consecutive trials. The maximum number of trials to reach the learning criterion was 60.

Test trials. When the children reached the criterion, 5 types of test trials (Figure 1B-F) were interspersed pseudo-randomly, with a mean frequency of 1 every 5 training trials. Two trials of each type were conducted, using the B and D start positions. These trials were not reinforced (the participants were not allowed to raise the container) and ended after the first choice.

Removal of the guidance-cue. These tests evaluated whether the subjects were able to solve the task in absence of the guidance.

Place-guidance dissociation. The guidance-cue was placed on the arm that occupied the location opposite to the goal place. This permitted dissociation of the choices made on the basis of the cues provided by the model and/or the room (allocentric responses) from those based on the guidance-cue (egocentric responses).

Removal of the peripheral cues. All of the cues provided by the model, including the guidance-cue, were removed to determine whether the children could locate the goal on the basis of the remaining information (i.e., the geometrical features of the model and/or the cues in the room).

180° model-rotation. The guidance cue was removed, and the model with the maze and the peripheral cues were rotated 180° relative to the room and to the participant, who remained in the same position as the training position. These trials allowed us to determine whether the children preferred to use the information provided by the model or that provided by the room.

Change of participant position. These trials were preceded by a disorientation procedure. The experimenter blindfolded the child and turned him/her around and then led him/her to a chair that was placed on the side of the model opposite to that occupied during training. The model with the maze and the peripheral cues remained in the same position relative to the room, but the guidance cue was removed. These trials enabled us to determine whether the participants used allocentric or egocentric strategies.

Pretraining, training, and test trials were conducted in a single day.

Data analysis

Performance was evaluated by the number of trials to reach the criterion, the percentage of correct trials during training, and the

percentage of choices for each arm during the test trials. Data were analyzed using one-way ANOVA and mixed ANOVA. Multiple comparisons were corrected by Bonferroni. Data are reported

as the mean±SEM. *P* values <.05 were considered statistically significant. All statistical computations were made with SPSS 17.00 statistical software.

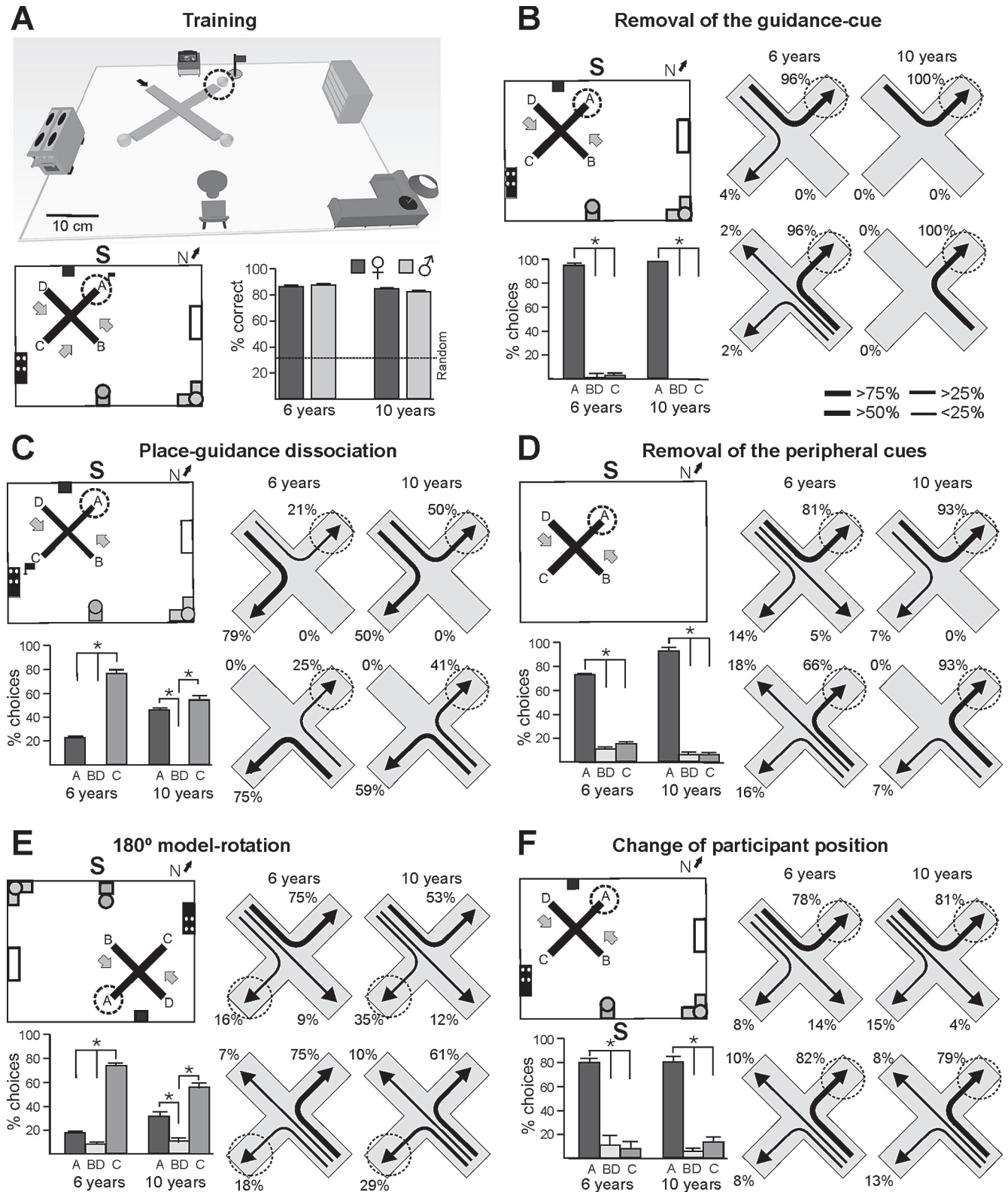


Figure 1. Orientation strategies in a situation of consistency among the frames of reference

Results

Training

All of the children quickly learned to solve the task, reaching the acquisition criterion with a mean of 19.66 trials. No significant between-subject differences were observed (one-way ANOVA Gender \times Age; Age: $F(1, 44) = 2.890, p = .096$; Gender: $F(1, 44) = 0.938, p = .338$; interaction: $F(1, 44) = 12.264, p = .149$).

We analyzed the number of correct choices with a mixed ANOVA with Age and Gender as between-subject factors and the Start-arm as a repeated measure. The results showed that none of the variables were statistically significant (Age: $F(1, 44) = 3.846, p = .061$; Gender: $F(1, 44) = .197, p = .659$; Gender \times Age: $F(1, 44) = .662, p = .420$; Start-arm: $F(2, 88) = .413, p = .663$; Start-arm \times Gender: $F(2, 88) = 1.442, p = .242$; Start-arm \times Age: $F(2, 88) = 2.761, p = .069$; Start-arm \times Age \times Gender: $F(2, 1, 88) = .163, p = .850$; Figure 1A).

Test trials

Figure 1B-F shows the percentage of choices for each arm by age-group. The trajectories represent the percentage of choices (relative thickness of the arrows) from each start-arm (B and D). In the histograms, choices to arms B and D are averaged. The data of each test trial were analyzed using mixed ANOVA that included the Start-arm and the Chosen-arm as repeated measures and Age and Gender as between-subjects factors. Because the variables Gender and Start-arm did not show a main effect or statistically significant interaction (all p values $>.323$), they were excluded from the model for the remaining analysis. Consequently, further analysis included Age as a between-subjects factor and the Chosen-arm as a repeated measure. No significant differences were found in the interaction Chosen-arm \times Age in the *Removal of the guidance-cue* [F Greenhouse-Geisser (1.497, 68.874) = 1.491, $p = .233$], *Removal of the peripheral cues* [F Greenhouse-Geisser (1.674, 76.986) = 3.145, $p = .057$], or *Change of participant's position* test trials [$F(1, 46) = 2.333, p = .134$]. Consequently, data for the two age-groups were collapsed for comparisons. In these three tests, the subjects chose the arm that led to the goal place (place-arm) significantly more than the other two arms (all p values = .0001); no significant differences were observed between the latter two arms (all p values $>.074$, Figure 1B, D, F).

The effect of the interaction Chosen-arm \times Age was statistically significant in the *Place-guidance dissociation* and the *180° model-rotation* test trials [all $F(1, 46) > 3.892$, all $p < .049$; Figure 1C, E]. In the *Place-guidance dissociation* test, the 6-year-old children showed a significant preference for the arm that was signaled by the guidance-cue relative to the other two arms (Guidance-arm \times Place-arm $p = .010$; Guidance-arm \times Others $p = .001$) and for the arm that previously led to the goal place relative to the third arm ($p = .005$). By contrast, the 10-year-old children showed a significant preference for the place-arm ($p = .001$) and for the arm that was signaled by the guidance-cue ($p = .001$) relative to the third arm in the *Place-guidance dissociation* test; no significant differences were observed between the guidance- and the place-arms ($p = .823$). In the *180° model-rotation* test, 6- and 10-year-old children showed a significant preference for the arm that was defined by the frame of reference provided by the room relative to the other two arms (6-year: both p values = .001; 10-year: both p values $<.002$; Figure 1E). However, no significant differences were observed between the place-arm and the third arm among the 6-year-old

children ($p = .159$), whereas the 10-year-old preferentially selected the place-arm rather than the third arm ($p = .001$).

EXPERIMENT 2:

ORIENTATION STRATEGIES OF 6-10-YEAR-OLD CHILDREN AND ADULTS IN A SITUATION OF INCONSISTENCY BETWEEN THE FRAME OF REFERENCE PROVIDED BY THE SMALL-SCALE MANIPULATORY SPACE AND THAT PROVIDED BY THE BODY AND THE ROOM

Method

Participants

A total of 88 subjects participated in this experiment. They were divided among the following four age-groups: 6 years ($n = 16$), 8 years ($n = 16$), 10 years ($n = 36$) and 19 years ($n = 20$). The number of females and males was the same in all of the groups.

Training

The apparatus and testing room were the same as those in Experiment 1, but the guidance-cue was not present in this experiment. Training was also the same except that while the participants had their eyes closed, the entire model (including the board, the peripheral cues and the maze) was rotated. Nonetheless, the start-arm was always positioned in front of the subject (S in Figure 2A), who remained in the same place throughout training. As this procedure made the frames of reference provided by the body and the room irrelevant, only the visual cues that were intrinsic to the model were useful for task solution.

Test trials

Four types of test trials were intercalated in a pseudorandom order, with a mean frequency of 1 every 5 post-criterion training trials (Figure 2B-E).

New start-position. The maze was displaced within the small scale in such a way that the end of one arm occupied the place that was reinforced during the training trials. The grey maze in Figure 2B indicates its position during training. The subjects started in a novel position and had to implement new routes (i.e., place strategies).

Disorganization of the peripheral cues. The location of the cues in the model was modified such that the spatial relationships with every other cue and relative to the goal-place changed. These trials tested whether the participants employed a place strategy on the basis of the information provided by the cue configuration.

Removal of the peripheral cues. These trials permitted us to test whether the participants were able to solve the task exclusively on the basis of the information provided by the geometric features of the model without the peripheral cues.

Maze displacement and peripheral cue removal. The maze was displaced to the center of the board, and all of the cues were removed. These trials tested whether the subjects employed an orientation strategy based on information other than the geometry, the cue-configuration or a particular cue.

Two trials of each type were conducted (start-arms B and D were used for the *Disorganization of the peripheral cues* and *Removal of peripheral cues* trials; start-arm E for the *New start-position* trials; and start-arms W and Z for the *Maze-displacement and peripheral cue removal* trial).

Data analysis

The recorded variables and data analysis were the same as those in Experiment 1, except the comparisons for the test trials were performed using orthogonal planned contrasts.

Results

Training

The results showed important differences in the percentage of subjects who reached learning criterion within each gender- and

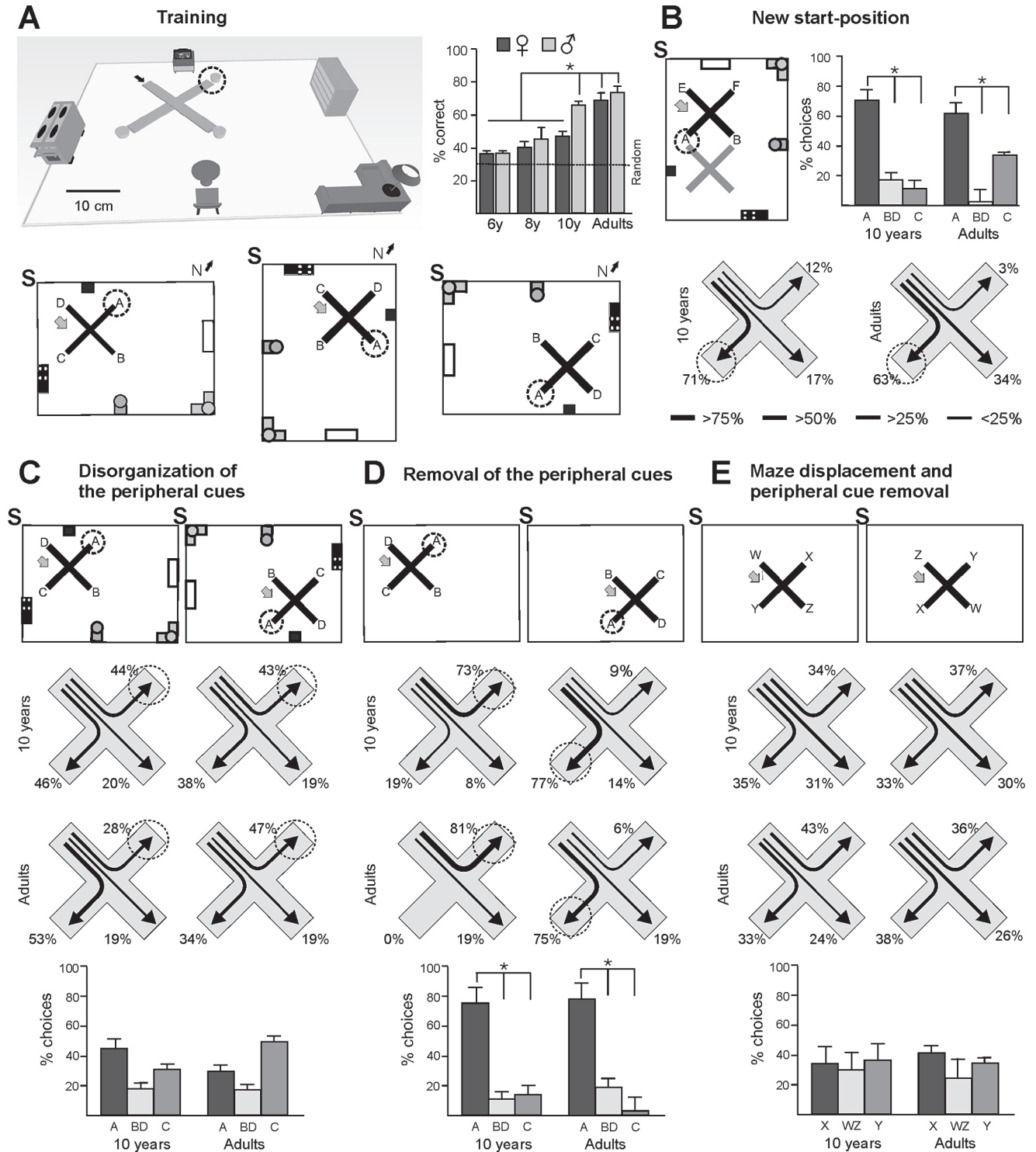


Figure 2. Orientation strategies in a situation of inconsistency between the multiple frames of reference

age-group (6 years: females 0%, males 0%; 8 years: females 12.5%, males 25%; 10 years: females 27.78%, males 66.67%; adults: females 70%, males 90%). The mean number of trials to reach the criterion was 44; no significant between-subjects differences were observed (one-way ANOVA Gender \times Age; Age: $F(3,84) = 2.300, p = .145$; Gender: $F(1,86) = 1.500, p = .229$; interaction: $F(3,80) = 2.100, p = .153$). The percentage of correct responses was analyzed with a mixed-model ANOVA with Gender and Age as between-subject factors and the Start-arms as the repeated measure. The Start-arm did not show statistically significant main effects or interactions (all p values $>.050$) in any case; thus, it was eliminated from further analysis. Therefore, further analysis included Age and Gender as between-subject factors. This analysis showed a significant main effect of Age [$F(3,80) = 11.853, p = .001$] and a non-significant effect of Gender [$F(1,80) = 2.674, p = .106$] and interaction [$F(3,80) = 1.337, p = .268$]. The post-hoc analysis of the differences in the percentage of correct responses between males and females within each age-group only showed significant differences in the 10-year-old group ($p = .004$, Figure 2A). The comparison between age-groups within each gender-group showed that the only significant differences among females appeared between the adults and every other age-group (6 years, $p = .004$; 8 years, $p = .025$; 10 years, $p = .020$). For males, significant differences were found between the adults and the 6-year-old children ($p = .0001$) and between adults and the 8-year-old children ($p = .013$), but not between the adults and the 10-year-old children ($p = .980$).

Test trials

Figure 2B-E shows the percentage of choices for each arm by age-group (choices to arms B-D and W-Z are averaged in the histograms). The small number of 8-year-old children who reached the learning criterion does not permit statistical comparisons; thus, only the results of the groups of adults and 10-year-old children are discussed. Mixed ANOVAs were employed to determine whether there were statistically significant differences in the chosen arm using Age and Gender as between-subjects factors and the Start- and the Chosen-arms as the repeated measures. These analyses were performed for the four types of tests. In all of the tests, the 1-, 2- and 3-order interactions (all p values $>.141$) and the main effects of Gender, Age and Start-arm ($p >.132$) were not statistically significant.

The main effect of the Chosen-arm only showed significant differences in the *Removal of the peripheral cues* and in the *New start-position* test trials [all F Lower limit (1,27) > 13.449 , all p values $<.001$]. The main effect of this variable was not significant in the *Disorganization of the peripheral cues* [F Lower limit(1,27) $= 1.662, p = .208$] and the *Maze displacement and peripheral cue removal* [F Assumed sphericity (2,54) $= 0.806, p = .452$, Figure 2B-E] tests. Orthogonal planned contrasts adjusted by Bonferroni correction were used to detail the significant differences.

In the *Removal of the peripheral cues* and the *New start-position* tests, we analyzed whether the percentage of choices for the place-arm differed from that for the two other arms and whether there were significant differences between the percentage of choices for these two arms. Whereas the contrast place-arm vs other arms was statistically significant in both tests [all $F(1,27) > 17.127$, all $p <.0001$; Figure 2B, D], the comparison between the incorrect arms did not show significant differences [$F(1,27) > 0.072, p <.790$, Figure 2B, D].

The current results show that throughout development, children display an increasing flexibility in the separate and cooperative use of egocentric and allocentric frames of reference to accurately locate a goal in small-scale environments. However, the ability to employ these strategies depends on a number of factors, such as the disorientation procedure or the possibility of establishing spatial relationships between the different frames of reference. In fact, when the frames of reference provided by the room and by the subject become inconsistent with that provided by the manipulatory environment, the performance decays relative to the situation in which multiple frames of reference can be used cooperatively to locate the goal.

Experiment 1 shows that when the frames of reference provided by the model, the room and the body are consistent and the goal location is directly signaled by a guidance-cue, 6- and 10-year-old children quickly learn to solve the task, with no differences by age or gender. However, children change their strategies throughout development. They prefer to use a guidance strategy at age 6, whereas they equally use the guidance-cue and strategies centered on the room or in the small-scale model at age 10 (Figure 1C). In the absence of guidance, 6- and 10-year-old children preferentially use the frame of reference provided by the room rather than strategies based on the model (Figure 1D-E) or the body (Figure 1F). These results agree with those reported by Nardini and colleagues (2006), who showed that 6-year-old children can accurately locate an object in a model when the frames of reference centered on the model and on the room are consistent. This suggests that the effect of consistency with the room is stronger than the body-centered strategies. During training, the frame of reference provided by the room is redundant with that of the model. This may explain the preference for the former, given that the information it provides is more reliable, stable and salient (Gouteaux & Spelke, 2001; Learmonth, Nadel, & Newcombe, 2002; Wang & Spelke, 2000). However, although trained in a situation of consistency between different frames of reference, 10-year-old children begin to use some information provided by the model. This is demonstrated by their performance in the *180° model-rotation* test, as they preferred the arm that led to the goal-place defined in relation to the cues of the model rather than the third arm (Figure 1E).

In Experiment 2, we analyzed whether 6- to 10-year-old children and adults are able to solve the task exclusively on the basis of an allocentric frame of reference intrinsic to the model, i.e., when the other frames of reference are not reliable. With this aim, we removed the guidance-cue and made the relationships of the room and the subject inconsistent with the goal-place by rotating the model between training trials. The results showed that 6-year-old children were not able to reorient by means of model-centered strategies. It is likely that the main difficulty resides in the coexistence of multiple, conflicting frames of reference (Newcombe & Huttenlocher, 2003; Nardini et al., 2006). In addition, the subjects must inhibit the responses based on the frame of reference provided by the room, which is the preferred frame of reference in absence of a guidance-cue, as demonstrated in Experiment 1. Similarly, Nardini and colleagues (2006) observed that performance worsened when the frames of reference of the model and the room were not consistent.

Similar to adults, 10-year-old children showed a greater flexibility in the use of spatial strategies as they began to rely on the

information provided by the manipulatory environment to reorient. The test trials showed that the children who learned the task used the cues of the model in a relational manner (Eichenbaum, 2000). This was evidenced by their ability to implement new trajectories when the maze was displaced within the model and the cues were present (Figure 2B) and by their inability to reorient when the configuration formed by these cues was disorganized (Figure 2C). These results are inconsistent with those by Nardini and colleagues (2006), which showed an earlier emergence (5 years) of the ability to use strategies centered on the model and independent of the room and of their own position. However, because their procedure lacked tests that manipulated the cue configuration in the model, it does not permit an unambiguous conclusion concerning whether the 5-year-old children were using a relational (allocentric) representation of those cues.

The 10-year-old children who learned this task also used the geometric information provided by the model. When all of the peripheral cues of the model were removed and the maze remained in the same place, the subjects continued to locate the goal-place (Figure 2D). In addition, in the test in which the geometric information of the model did not permit the subjects to locate the goal (Figure 2E), they selected at random. These results confirm that the ability to use the geometric information to orient appears later for manipulatory environments than in locomotor-navigational environments. When using small-scale models, the disorientation procedure implies rotating the model while the participant remains in the same position, which requires more complex mechanisms for reorientation (Gouteux et al., 2001; Hupbach & Nadel, 2005; Lourenco & Huttenlocher, 2006).

We did not find sex-based differences in the solution of the task in Experiment 1 and only a slight difference in Experiment 2 at age 10. Sex-differences in spatial abilities are a conflicting issue, yielding different conclusions depending on the specific

task used (Cimadevilla, Conejo, Miranda, & Arias, 2004; Postma, Jager, Kessels, Koppeschaar, & Honk, 2004; Voyer, Voyer, & Bryden, 1995). In the current study, the 10-year-old boys showed more ability than girls to solve the task. This difference, which disappears in adults, could be due to a gender-dependent time course in the emergence of allocentric frames of reference centered on the model.

Learning this spatial task likely involves different abilities and strategies that depend on different brain regions, including the hippocampus, parietal cortex and areas of prefrontal cortex (Eichenbaum, 2000; Newcombe & Huttenlocher, 2003). The developmental changes observed in the present study could reflect the degree of maturation of these structures. The ability to locate the object when the frame of reference intrinsic to the model is consistent with those based on the room and the body position (Experiment 1) is present at age 6 and could depend on the dorsal visual stream and the posterior parietal cortex (Milner & Goodale, 1995), which reaches the adult volume earlier than the hippocampus (Lenroot & Giedd, 2006). The emergence of the ability to use a frame of reference intrinsic to the model and independent of the subject's perspective at age 8-10 could be associated with the maturation of the hippocampus, which plays a critical role in the construction of spatial allocentric representations (Burgess, Jeffery, & O'Keefe, 1999; Salas, Broglio, & Rodríguez, 2003). Similarly, the ability to inhibit the incorrect frames of reference centered on the body or the room likely depends on the maturation of the prefrontal cortex (Diamond, 1990; Goldman-Rakic, 1987). Further neuroimaging or clinical studies could help to confirm this hypothesis.

Acknowledgments

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