Defining Spatial Boundaries: A Developmental Study

Eugenia Gianni and Sang Ah Lee

Abstract Although the capacity to navigate by environmental boundaries has been widely documented, the perceptual and physical factors that define a boundary have yet to be defined. In this study, we tested children's navigation in spatial arrays consisting of 20 freestanding objects with varied inter-object spacing and length. Children begin to successfully compute locations using aligned (but discontinuous) object arrays around the seventh year of age. Our results suggest a late-emerging capacity of extrapolating geometric information from discontinuous structures.

Keywords Boundaries • Navigation • Freestanding objects • Geometric information

1 Introduction

Humans and animals possess impressive capacities of navigating and orienting in familiar and unfamiliar environments. It is generally believed that they do this by means of storing global spatial representations of the surrounding environment, so-called cognitive maps (O'keefe and Nadel 1978). A wide range of studies, from behavioral to electrophysiological, to computational models (Hartley et al. 2014) have shown that one of the primary inputs to place coding are environmental boundaries. When rats found food in one particular corner of a rectangular arena, upon disorientation they tended to limit their search to the target corner and the

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geometrically identical (rotationally symmetric) diagonal corner with the same frequency, even when the target corner could be disambiguated by means of a featural cue such as color or visual pattern (Cheng 1986). Interestingly, almost all animals have shown to behave similarly, including human children (Hermer and Spelke 1994; Lee and Spelke 2010) Even in human adults, boundaries and object/landmark features are processed separately during navigation and respond to different neural and behavioral mechanisms (Doeller and Burgess 2008; Doeller et al. 2008). While boundary-based navigation is well-documented even across species, the factors that define surfaces as boundaries have yet to be determined. Studies with children have started to answer this question by manipulating the physical and visual properties of spatial boundaries. They have shown that preschool children can use boundaries to navigate as long as they are 3D and extended on the ground-plane, while they cannot use 2D forms and geometric arrays made up of three or four free-standing objects (Gouteux et al. 2001; Lee and Spelke 2008; Lee and Spelke 2011).

What is the fundamental difference between an array of objects and an array of walls? Previous work has shown that even two-year-old children succeed in using surfaces even if they are segmented into four distinct 100 or 80-cm-long walls in a rectangular array (Lee et al. 2012) as long as they are opaque (Gianni and Lee (in preparation)). However, it is still not clear how their use in navigation relates to their capacity of preventing movement (Kosslyn et al. 1974) or how their length and solidity/continuity factor plays a role into their conceptualization as boundaries (Lee et al. 2012), and finally if their conceptualization is submitted to fundamental changes over the course of development (Fig. 1).

In our study we addressed these questions by testing children from 4 to 9 years old in four different arrays consisting of twenty free-standing objects (see Fig. 2). In Experiment 1, the objects were arranged in a rectangular fashion with an inter-object spacing of 16 cm. In Experiment 2, the objects were arranged more densely together to form four segments with an inter-object space of 8 cm. In these two conditions the objects were freestanding and discontinuous, but sufficiently dense to underline the geometric figure and to prevent children's movement. In Experiment 3, objects were aligned to form a rectangular array of 4 continuous walls of 50 cm, and in Experiment 4 they were rearranged into two longer continuous walls (100 cm long).

2 Methods

2.1 Experimental Setting

Experiments took place within a round room formed out of black curtains (2.10 m diameter) hanging from the ceiling on a circular track. The entrance to the room (created by the curtain's latch) was masked in order to avoid spatial cues.

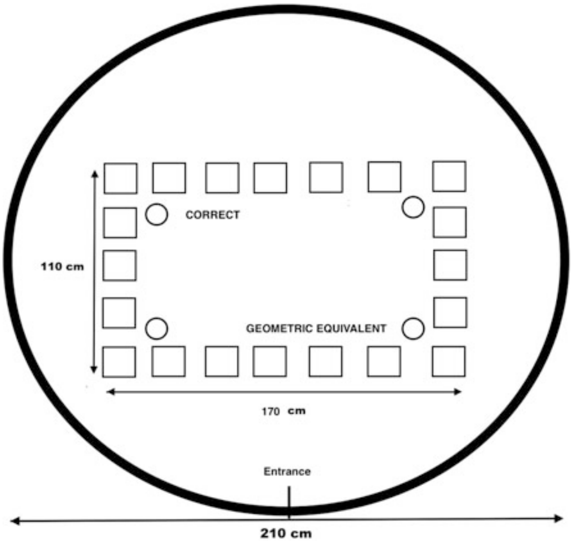

Fig. 1 Experimental setting, schematic view from *above*. Inside a *black round curtain* 20 free-standing objects (here schematically arranged as in Exp. 1, Fig. 2a) were placed as to form a *rectangular arena* (170 × 110) cm, outside perimeter). If during the game the sticker was placed in the *upper-left corner* (Correct), the opposite *diagonal corner* was indistinguishable for a disoriented subject and therefore labeled as 'Geometric Equivalent.' A majority of choices for both correct and geometric equivalent corners, after disorientation suggested the subject had correctly encoded and used the geometric properties of the array to reorient

4 symmetrically LEDs on the ceiling provided uniform lighting. The experimental arrays were placed at the center of the room, on a grey-colored non-slip floor. 4 inverted cups were placed at the four corners of the arena and served as hiding places for stickers (Fig. 1).

2.2 *Experimental Apparatus*

20 while plastic parallelepipeds, 30 cm high, 10 × 10 cm wide, were arranged as to create a rectangular arena (170 × 110 cm, outer perimeter). In Experiment 1, they were uniformly aligned along the perimeter with an inter-object space of 16 cm (Fig. 2a). In Experiment 2, the objects were arranged along the same 170 × 110 cm perimeter as to create four distinct 80 cm segments, with an inter-object space of 8 cm (Fig. 2b). In Experiment 3, objects were arranged to create four distinct compact walls of equal length (50 cm) (Fig. 2c). Finally, in Experiment 4, the objects were compactly arranged to form two 100 cm walls (Fig. 2d).

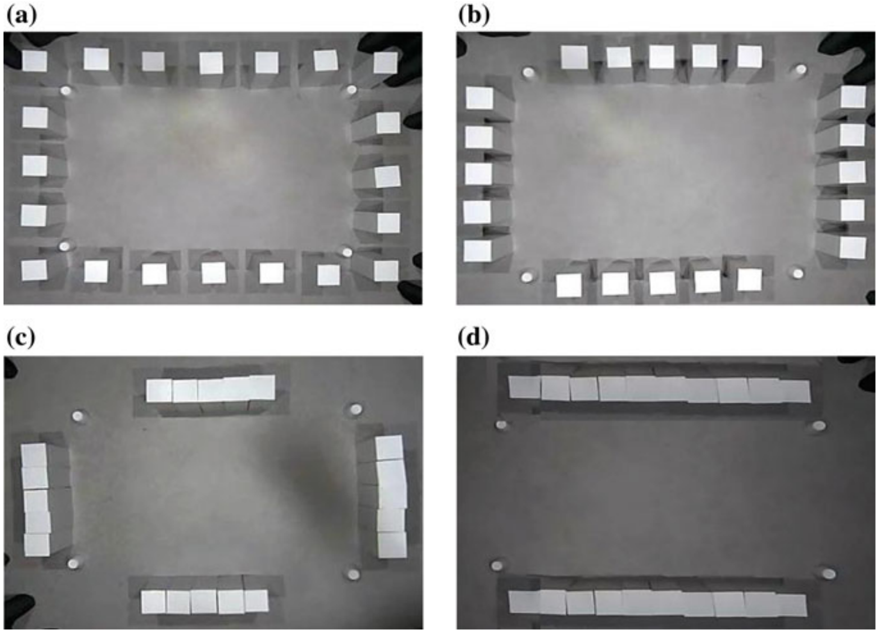

Fig. 2 Arrays made up of twenty freestanding objects: **a** Uniformly arranged, 16 cm apart. **b** Arranged more densely, 8 cm apart. **c** Continuous, four walls 50 cm long. **d** Continuous, two walls 100 cm long

2.3 Participants and Experimental Procedures

89 healthy children, 48 males and 41 females, ranging from 48 to 119 months (4–9 years old) were tested in this study. They were recruited from daycares and recreational centers in the area of Rovereto and the surrounding area of the Province of Trento. They voluntarily came to the laboratory accompanied by their parents. Before the test they were let playing in the toy-area of the laboratory for about 10 min. During the test they were accompanied by the experimenter to the experimental room and let step into the center of the arena. The experimenter then hid a sticker in one of the four cups placed at each arena's corner, taking care the child was paying attention. The child was instructed to be about to play a hiding and finding game where he had to exactly locate the sticker after disorientation in order to win it. The experimenter then blindfolded the child and let him rotate on its place for 10 s in either directions for disorienting. He then removed the blindfold and let the child search for the sticker. First choices were recorded. The procedure was repeated for four trials.

3 Methods

3.1 Experiments 1 and 2. Discontinuous Objects

Analyses were conducted by computing the average proportion of geometric searches (at the correct corner + geometric equivalent corner; see Fig. 1). Since no significant effect of condition across the first and the second experiment was found, data from experiment 1 and experiment 2 were collapsed. A univariate ANOVA was used to compare the performance of 4–6 year-olds (48 subjects) with performances of 7–9 year-olds (34 subjects). A significant main effect of age group was found (F(2) = 4.234; p = 0.018). T-tests against the level of chance (0.5) showed that 4–6 years old children did not perform above the level of chance (T (47) = 1.091; p = 0.281), while children ranging from 6 to 9 did (T(33) = 5.583; $p < 0.001$). There were no significant effects of sex or condition ($F < 1$, n.s.) (Fig. 3).

3.2 Experiment 2 and 3. Continuous Surfaces

Experiment 3 and Experiment 4 were designed to test continuous surfaces of two different lengths, while keeping total number of objects (surface area) equal across all four conditions. Subjects were tested in a within-subjects design and the order was counterbalanced across subjects (each subject was alternatively submitted to either experiment 3 or 4 first). So far only 7 children between the age of 4 and 5 years old have been tested. A repeated measures ANOVA looking at geometric search in the two conditions (within-subjects factor) and two between-subjects factors—sex and experimental order (either experiment 3 or 4 first)—was used to explore these preliminary data. A significant main effect of condition was found (F(1) = 15,364; p = 0.017). Exploratory tests against the level of chance revealed that children did not perform significantly above chance in Experiment 3 (T(6) = 1.922; p = 0.103) while they did perform above the level of chance in Experiment 4. (T(6) = 4.804; p = 0.003) (Fig. 4).

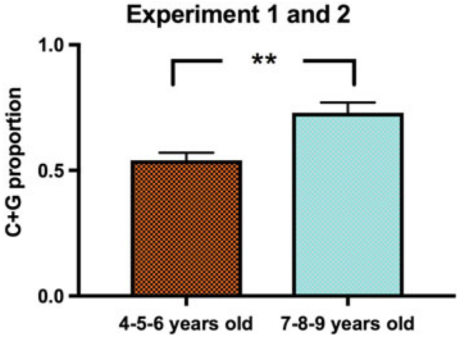

Fig. 3 Mean performance for 4, 5, 6 years old and 7, 8, 9 years old groups. *Error bars* represent standard errors. ** $p \leq 0.01$

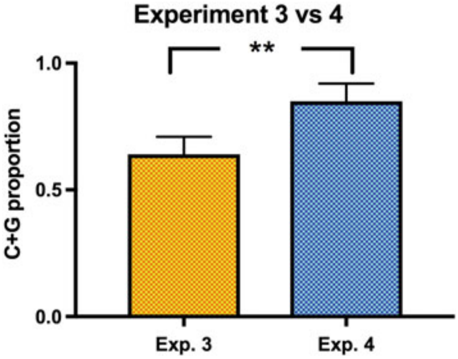

Fig. 4 Mean performance in Experiments 3 and 4. *Error bars* represent standard errors. **p ≤ 0.01

4 Discussion

Considering experiments 1 and 2, our results suggest that children develop the capacity of using discontinuous walls around the 7th year of age, considerably later then continuous walls (Hermer and Spelke 1994). Indeed previous studies have shown that children developed the capacity to reorient using continuous boundaries at the age of two years-old, even if the boundaries were segmented (Lee et al. 2012) and of low visibility (Lee and Spelke 2011). Previous studies have shown children fail in orienting towards structures made up of three (Gouteux et al. 2001) or four free-standing objects (Lee and Spelke 2008; Lee and Spelke 2011) but they left room for hypothesizing whether children failed because either the boundary were not sufficiently visible in their geometric shape or because they did not sufficiently prevent movement. In our experiment we show for the first time that, as long as the structure is sufficiently dense to prevent movement, and sufficiently visually robust to underline the geometric shape, children still fail until the age of seven. The failure to navigate by the geometry of the discontinuous object arrays might be explained by a later-emerging capacity of integrating information from qualitatively different sources, such as boundaries and landmarks, which are separately processed in navigation (Doeller et al. 2008). Such a conclusion might be consistent with the finding that the capacity of children to integrate a feature such as color and boundaries' geometric structure to correctly orient is acquired only between the 5th and the 7th year of age (Hermer-Vazquez et al. 2001).

Moreover preliminary data in experiments 3 and 4 show that younger children are not able to use 50 cm walls but perform well with 100 cm walls, putting into context previous work showing success with 100 or 80-cm-long walls (Gianni and Lee (in prep.); Lee and Spelke 2011). The relevance of wall length should be further explored by taking into account factors such as the child's physical size and interaction with the objects/boundaries, as they may reveal the threshold at which children begin to perceive the wall as qualitatively different from an object.

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