Children's representation of spatial boundaries

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Year 2017/2018

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“I believe that the brain has evolved

over millions of years

to be responsive to different kinds

of content in the world.

Language content, musical content, spatial content,

numerical content, etc.”

Howard Gardner

ACKNOWLEDGEMENTS

First of all, I want to thank my Supervisor, Sang Ah Lee, for allowing me to spend three years doing a wonderful research, for being so enthusiastic and so lovely and patient at the same time. I also thank my OC members, Manuela Piazza and Giorgio Vallortigara, for following me during these years and providing important suggestions. I want to thank my lab, the BabyLab, and my lab members, especially Marilina and Rachel and Anna Gui (previous member), for the collaboration we set up, the suggestions they gave me and for their friendship. Finally, a special thanks goes to my parents and to my brother inexhaustible source of love and inspiration.

Abstract

Finding the way home, orienting into familiar and unfamiliar environments, computing our place and position with reference to internal and external cues are essential everyday tasks for animals. It is generally acknowledged that these tasks are accomplished by the brain by means of the internal formation of complex spatial representation, the so called "cognitive maps". How the brain can form these cognitive maps is a very debated issue in the field of neuroscience. An important stream of research tried to find out what the main environmental features the brain tends to store while navigating are. In order to investigate this, researchers have observed the behavior of animals after being disoriented in a familiar environment. The reorientation paradigm turned out to be a very interesting tool to study spatial cognition because it allows researchers to figure out which environmental components the animals remember and rely on in order to find their way after they have lost track of their heading and position. Experiments with both human adults, children and nonhuman animals have shown that an important feature of the environment the subjects tend to store to reorient is the geometry of the boundaries' layout (e.g., room shape). Children from as early as 2 years of age have been shown to be able to use the geometric shape of the spatial layout by searching an object hidden in one corner of a rectangular enclosure both in the correct corner and in its geometric equivalent. But which perceptual and physical factors define spatial boundaries? Which geometric components of boundaries are children most sensitive to? How are the same geometric components used in other spatial tasks such as map reading?

In our studies we tried to answer these fundamental questions. In our first study we investigated whether children are sensitive to boundaries that constitute either physical or visual obstacles. To this aim we tested children in a reorientation task with both an arena made up of transparent surfaces and an arena made up of opaque surfaces. By using transparent surfaces, we were able to minimize the visually occlusive component of the boundaries but leave intact its physical component. Opaque boundaries presented, instead, both the visual and physical components. In our second study, we further investigated how does the material and visual appearance of boundaries affect navigation by testing children in an arena made up of 20 closely-aligned objects. In this experiment we made the surfaces visually discontinuous, but the configuration of objects was made sufficiently dense to prevent movement and to underline the geometric structure. In our third study, we asked which components of the Euclidean geometry are children most sensitive to while navigating by geometric boundaries and making a map task. In particular we investigated the use of distance and length both in a reorientation task and a map-placement task.

The results showed that important developmental changes occur in children's representation of spatial boundaries and of their geometric components. In particular children became proficient at using transparent surfaces only at the age of five and they start using boundaries made up of closely-aligned objects at the age of seven. At the same time, we showed that the young children (36 to 42 months) reorient correctly in a disorientation task by using the geometric property of distance, rather than length. The same group of children were shown not to be able to use distance nor length in a map task, while they showed the ability to use angle.

These results suggest that not all kinds of boundaries are processed equally by children and that their visual aspect might be more important that their property of being obstacles to movement, particularly early in development. They are important because they inform of which material and physical properties of boundaries children are most sensitive to and they can help understanding how to design and build safe environments for children. Moreover, they suggest the geometric property used by young children to reorient is distance, essentially contributing to the wide debate on how children and animals could solve the reorientation task. Finally, they showed that the use of geometric properties in a reorientation task and in a map task might have two different developmental trajectories, suggesting these two competences might be mediated by two different systems and providing an important insight into the development of geometric competences in children.

General Introduction

1. Spatial cognition and the brain

It is acknowledged that many vertebrate and invertebrate species possess sophisticated innate abilities to navigate in space and to orient in the surrounding environment. The evidence shows that bees can compute their path towards particular targets and back to the hive with surprising accuracy (Gould 1986), that homing birds are provided with precise capacities of orienting while flying over enormous distances (O'Keefe & Nadel 1978), that homing pigeons are able to find their way home after being released even many thousand miles far away from their nest (Watson & Lashley 1915), that rats have the ability to remember significant locations basing on allocentric coordinates (Tolman 1984), that chimps can adopt refined spatial strategies while searching for a food-reward (Menzel 1973, O'Keefe & Nadel 1978). Many thousands of publications on this topic and one Nobel prize awarded (Burgess 2014) made spatial cognition one of the most relevant and debated issues in the neuroscience field. Researchers agree on the fact that complex brain representations of the environment lie at the basis of spatial abilities, the so called "cognitive maps". These maps allow humans and animals to identify their position within the environment, to quickly map novel environments and to orient throughout familiar ones (Tolman 1948, O'Keefe & Nadel 1978).

How humans' and animals' brains form these kind of representations is a very debated issue (Derdikman & Moser 2010). Which environmental elements does the brain preferably encode in order to store significant locations? (Gianni 2015) How does it integrate multiple inputs in order to form an extensive, cohesive representation of the environment (Burgess 2006)? How do children develop spatial abilities (Spelke, Lee & Izard 2010; Bullens et al. 2010)? Which kind of spatial components are we most sensitive to and how does it change over development (Lee, Sovrano & Spelke 2012)? In the past years researchers in the field of spatial cognition tried to provide an answer to these challenging questions (Cheng et al. 2013). In our studies we sought to investigate which environmental components children mainly store while navigating and how it changes over development.

2. The importance of geometry in navigation

As we said, humans and animals possess impressive capacities of moving and orienting into familiar and unfamiliar environments. In order to do this, they have to be able to combine multiple inputs coming from different sources: internal vestibular information, environmental information coming from scenes' layout, positions of specific targets, positions of distal and/or proximal landmarks and the tracking of travelled distances and directions (Burgess 2008). Those inputs are likely to be integrated into complex environmental representations, the so called "cognitive maps" (Tolman 1948, O'Keefe & Nadel 1978), that are supposed to guide the animals in their path by representing and updating the external spatial reference frame and the animal's position within it (Eichenbaum et al. 1999). How the brain produces these kinds of representations, from the level of specialized neurons to the level of functional network systems, is a topic of wide scientific interest, with investigations implementing a wide range of research methodologies (Derdikman & Moser 2010; Hartley et al. 2014 for review).

The literature points to a combination of multiple, complementary cognitive mechanisms used to accomplish successful navigation across different species (Wang & Spelke 2002; Burgess 2008). It is acknowledged for example that insects and ants, in order to move and successfully find their way to the target and back to their home, employ a so called *path integration* mechanism (for reviews, see Biegler 2000; Collett & Collett 2002; Collett & Graham 2004; Etienne et al. 1998; Worsley et al. 2001) allowing them to exactly keep track of their travelled path by storing and updating the angular and Euclidean travelled distances from their starting position (for example the nest). This mechanism is used across many species such as birds, insects and mammals (Von Saint Paul 1982; Collett & Collett 2000; Mueller & Wehner 1988, 1994; Etienne 1996; Mittelstaedt & Mittelstaedt 1980; Etienne & Jeffery 2004) and is essential in many animals (and even humans) for finding their way home while travelling on long distances (Wang & Spelke 2002). However, such a mechanism is limited in precision and subject to cumulative errors. Moreover, it is no longer useful when an animal is displaced and then replaced in a familiar environment as it loses track of all the references it needs to restore its previous position. In this case, the evidence suggests the animals tend to restore their relationship to the environment through a process that is called *reorientation* (Wang & Spelke 2002; Cheng et al. 2013). Indeed, when the organism has lost track of its position and the visual scene before it entails a complex relationship of objects, layouts and landmarks, it has to rapidly and efficiently analyze all these elements (or a significant part of them) in order to accomplish successful, immediate reorientation. Many decades of research have established that one of the primary inputs for reorientation is the surrounding environmental *geometry* (Cheng, Huttenlocher & Newcombe 2013 for review). In particular, the geometry defined by the elements that mark the perimeter of the observed scene, namely environmental *boundaries* (Bird et al. 2010; Mou & Zou 2013).

The present research is focused on the use of boundaries for reorientation and map tasks in pre-school children. In particular we aimed at starting to investigate what is the "core" set of factors that qualify a boundary, as such, among the multiple stimuli the child can encounter on the navigable scene. In order to define such factors, we manipulated the shape, aspect and size of boundaries in various ways and observed how children use them to solve a reorientation task (Experiment 1, Chapter 1, Experiment 2, Chapter 2, Experiment 3, Chapter 3) and a map reading task (Experiment 3, Chapter 3). Moreover, in Experiment 1 and 2, as we acknowledge that important developmental changes (either maturational or experience-based) might occur during the pre-school phase (Hermer-Vazquez 1997; 2001; Bullens et al. 2010; Olson, Newcombe 2013), and that they might affect the way the child perceives and analyzes the surrounding set of inputs and navigational stimuli, we chose to study and observe children's behavior on a wide age range (2 to 7 years old and 2 to 9 years old in the first and second experiment respectively). This allowed us to be able to keep track of possible maturations and changes in the way children represent and use boundaries for navigation. Similarly, in Experiment 3 we chose to extend upon past studies, which focused on 2-year-old children (24 to 37 months) and tested children from two and half to three and a half years old (30 to 42 months old) in order to track possible developmental changes.

3. The use of geometric boundaries in navigation: behavioral studies

The first behavioral evidence for the importance of boundary-geometry in navigation comes from the work of K. Cheng (Cheng 1986). In his experiment, Cheng placed a hungry rat in a rectangular arena (120 X 60 cm) where the food was placed in a corner and allowed the rat to go eating the food, which was only partially buried at training. After some trials of training, he displaced the rat from the arena, moved the experimental setup and re-buried the food (completely), which was located in the same exact corner. Then he replaced the rat into the testing apparatus and observed his digging behavior. What he noticed was that the rat, even if the four corners were made clearly distinguishable from each other by panels that differed in texture, smell and brightness, tended to solve the task "up to rotational ambiguity". i.e. it dug in the target corner and in its opposite rotational one, lying on the same diagonal, with the same frequency. What did the two corners have in common? Even if the two corners were distinguishable by visibly different panels, odors and luminance effects, they presented the same geometric configuration to a disoriented subject; they had a short wall on the right and a long wall on the left (for example). The animals were thus likely to couple a "rudimental sense" of left and right with the perceived difference in length of the two rectangles' sides[1], what made them able to recognize, up to rotational ambiguity, the two correct geometric corners and dug at them to solve the task (Gallistel 1990; Sovrano et al. 2002; Sovrano & Vallortigara 2006).

From this experiment the author concluded that rats, while they were trying to orient for searching for the food, relied on the geometric configuration of the space as a privileged cue and ignored other, equally salient cues (Cheng & Gallistel 1984, Gallistel 1990). The use of geometry in reorientation was thus hypothesized to rely on an impenetrable "geometric module" mediating the computation of the principal axes of the environmental surroundings and matching them to the previously seen environmental shape to restore the correct orientation (Margules & Gallistel 1988, Gallistel 1998). Such a computation should have been encapsulated, task specific and impenetrable to "sensory data" such as smell, colour and other visual features (Gallistel 1990).

Starting from Cheng's discoveries, the same paradigm was applied to a wealth of different species, from some species of birds (Kelly & Spetch, 2001; Kelly, Spetch, & Heth, 1998, Kelly & Spetch, 2004), chicks, (Vallortigara, Zanforlin & Pasti 1990), fishes (Sovrano, Bisazza & Vallortigara 2002, 2003; Vargas, López, Salas, and Thinus-Blanc 2004), ants (Wystrach & Beugnon 2009), monkeys (Gouteux, Thinus-Blanc & Vauclair 2001) and finally human toddlers (Hermer & Spelke 1994, 1996; Huttenlocher & Vasilyeva, 2003; Lourenco, Huttenlocher & Vasilyeva, 2005). The use of features varied across different species, for example pigeons, chicks and fish were found to be able to conjoin geometric and non-geometric information and focus their search on the correct corner, but all species were found be able to correctly encode the geometric arrangement of space when presented an absence of distinctive features and, more importantly, learning the featural properties didn't overshadow the learning of geometry (Cheng, Newcombe 2005; 2006), as if the use of geometry was mediated by a separate, distinctive mechanism.

The primacy in the encoding of boundaries for spatial mapping was hypothesized to provide an adaptive advantage in navigation (Gallistel 1990; Vallortigara, 2009; Tommasi et al. 2012). While landmarks such as trees or buildings or surface properties, such as colour or texture, can easily undergo seasonal changes and disruptions, the 3D structure of the terrain is stable and fixed, and thus, reliable. Furthermore, boundary-based spatial mapping was argued to be computationally

[1] This is true even if recent accounts claim that animals and humans solve the task by computing the distances and directions from the borders of the arena (See Chapter 3, Discussion).

advantageous in that a set of large, extended surfaces, without the complexity and clutter of objects and features, can be represented with just a few points each (Gee et al. 2008; Silveira, Malis, & Rives 2008).

The use of geometry was not only studied and demonstrated in animal species, but also in human toddlers and adults. Hermer and Spelke (1996) tested 18 to 24 months old toddlers (and adults as well) in a white rectangular chamber with or without a distinctive bright blue panel marking one of the short walls. The task was similar to the one used for rats: while the child was attending, the experimenter hid a toy in one of the four corners, then he rotated the child while covering his eyes up to disorient him (usually four rotations were enough for the child to lose track of the target's relation to their initial position). Afterwards, the child was asked to recover the toy and first searches were recorded. In this task, both children and adults were shown to rely on the geometric configuration of the room in the "plain white condition" when the room was presented in absence of distinctive features that could disambiguate the two geometric equivalent corners. Instead, while adults confined their search to the correct corner in the "geometric+non-geometric condition", when the room was presented with the blue distinctive wall, children, as well as Cheng's rats, kept on dividing their search between the two geometric identical corners, ignoring the feature. Interestingly children presented the same behavior as rats, continuing to solve the task up to rotational ambiguity even when the experimenter tried to change the distinctive feature, i.e. if the walls were disambiguated by two large toys placed at two side walls, or when the corners were disambiguated by hiding boxes characterized by different distinctive patterns. Importantly, the children were shown to be able to use all of these features in oriented trials. If, on one side children differed from adults in their use of features, these experiments showed that a spontaneous capacity to use geometry occurs very early in children. The same early emerging capacity to use geometry was found in children, also when disoriented into rhombic (Hupbach & Nadel 2005), as well as triangular and octagonal rooms (Lourenco & Huttenlocher 2006; Newcombe et al. 2010), suggesting geometric sensitivity is not specific to the particular shape of the array, but rather, is related to the geometric relationships defined by the boundaries of the experimental room.

Successive findings showed that children (and some animal species), under different experimental circumstances[2] can also use features as reference points and combine the information

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[2] In particular the size of the enclosure seems to affect the use of features both in toddlers and in some animal species. The bigger the size, the more animal and children were found to be able to conjoin geometric and non-geometric

coming from features with ones coming from geometry. Conjunct evidence on the use of features from animals (for review see Cheng & Newcombe 2005; Lew 2011) and children (e.g. Learmonth, Nadel & Newcombe, 2002; Learmonth, Newcombe & Huttenlocher, 2001) thus served to cast doubt on the hypothesized modularity and impenetrability of the geometric module (Lew 2011, Newcombe & Ratliff 2007, Ratliff & Newcombe 2008). What is important to notice, however, is that in all these experiments aimed at investigating the use of features over geometry, both humans and animals were able to spontaneously rely on geometry when presented in rooms with no distinctive features, even in controlled rearing studies when they weren't previously familiarized with the geometric environment (Chiandetti & Vallortigara 2008), confirming geometry to be a fundamental, spontaneously used cue across many species; and validating the hypothesis of a philogenetically preserved, ancient system of spatial representation for navigation (Vallortigara 2009; Lee & Spelke 2010; Spelke, Lee & Izard 2010).

4. Neural representations of geometric boundaries

Neurophysiological and neuroimaging studies complemented behavioral evidence by showing the signatures of boundary-based navigation in the hippocampus and surrounding areas. By recording place cells[3] in different geometric shaped environments, O'Keefe and Burgess (1996) realized they fired at constant distance from the nearest walls. Importantly, while changes in the geometric shape of the boundary-surfaces affected place cell activations, changes in texture, material, and colors did not (Lever et al. 2002; Lever et al. 2009). Additionally, these neurons were shown to not be sensitive to free-standing objects, or even to object configurations placed at the center of the arena (Cressant, Muller & Poucet 1997; Zugaro, Berthoz, & Wiener 2001). In order to explain these

information for solving the task (Learmonth et al. 2008; Sovrano, Bisazza & Vallortigara 2007; Chiandetti & Vallortigara 2008).

[3] Place cells, recorded in the rat hippocampus fire at specific locations independently of the rat's orientation and direction. Each place cell has its specific place field, i.e. a place where, if the rat found itself in, let its firing rate increasing. Place cells have stable place fields and fire also if the rat is removed from its environment and then replaced into it. They are at the basis of the capacity of the rat to map the environment and exactly localize its position within it. (Moser, Kropf, & Moser 2008; O'Keefe & Dostrovsky 1971; O'Keefe & Burgess 2005; O'Keefe & Nadel 1978).

data, a model was built to account for the inputs the place cells receive from encountered boundaries. The BVC model assumes the place cells get inputs from so called “boundary vector cells”, particular cells that are tuned to respond to the presence of a barrier at a given distance along a given allocentric direction, independently from the rat's heading direction, with sharper tuning at shorter distances. The model also predicts that the addition of a barrier results in an addition of a place field relative to that barrier. Therefore, the boundary vector cells should encode the animal distance from geometric borders (Barry et al. 2006; Hartley et al. 2000, Lever et al. 2002). After being modelled, “border cells” were recorded in the rat's MEC (Medial enthorinal cortex) and in the para-subiculum. These cells, fired along proximal borders, were sensitive to shape changes and walls stretching (but not to changes in color or texture), and showed duplication of their firing fields after the insertion of additional extended barriers into the environment where the animals moved (Lever et al. 2009; Solstad et al. 2008). Cells with similar functions are likely to be found across different species, at least in mammals. For example, in nonhuman primates, the entorhinal cortex has been shown to house neurons that fire when the animal looks at the boundaries of visual scenes (Killian, Jutras, & Buffalo 2012). And the same cells are starting to be recorded in the human hippocampus and surrounding areas (Ekstrom et al. 2003).

Sensitivity to boundary geometry was studied in humans overall through neuroimaging studies. Doeller, King and Burgess (2008) scanned patients while performing an object location task in a virtual environment. In the exploration phase, participants explored the virtual environment in first person view-point by moving the joystick, while viewing and learning the respective positions of four different objects. Two objects presented a fixed position relative to a circular boundary and the other two presented a fixed position relative to a single intra-maze landmark (the landmark and the boundary were moved trial by trial in order to obtain this effect). During the test phase, the object appeared on the screen and subjects had to move to the location where they thought the object was. At every trial a feedback was given, such that the subject could re-collect the object and progressively learn the correct location. Functional MRI results showed greater hippocampal activation for the boundary-related learning and a greater dorsal striatal activity for the landmark related learning. Higher activation in both areas was related to greater increase in performance for both tasks. These results pointed to a specialization of the human hippocampus in boundary-based navigation.

Moreover, hippocampal activation was found out for visual imagery of navigable scenes. Bird et al. (2010) scanned patients while they were viewing (from movable viewpoints) a series of scenes made up of either vertical towers and/or horizontal boundaries and were asked to imagine standing within the environments. The number of enclosing boundaries was increased parametrically from scene to scene while keeping the same number of objects in the scene (5 objects, distributed among either vertical tower or horizontal walls). As a control condition, the colors were also changed through different blocks in order to create an effect of increasing color complexity. The results showed that activation of the hippocampus increased as a function of increasing the number of enclosing boundaries (and decreasing the number of towers) from the “0 walls” condition to the full “4 walls condition”. No effects were found in the hippocampus for increasing color complexity.

The hippocampal region, which specializes in processing boundaries, is likely to receive inputs from visual scene selective areas (PPA, RSC, OPA[4]), particularly for species that rely on vision (e.g. humans), as the same boundary-sensitivity was found in these areas for the passive viewing of global geometric elements of scenes. Epstein & Kanwisher (1998), first reported that the PPA maximally responded to images of landscapes scenes by scanning subjects with photographs of either scenes, faces and objects and found more elevated activity for global scenes. Afterwards, under the hypothesis of a PPA privileged encoding of the spatial layout, they compared the PPA activity when subjects were passively submitted to the view of furnished rooms, to the view of the same rooms when they were empty and to the bare set of furniture-objects without the background room. They found out that the PPA responded equally to the furnished and empty rooms, but not to the single furniture-objects when displaced on a blank background. Finally, they scanned subjects when they were viewing the same room image segmented, not segmented and segmented and rearranged in a non-meaningful way and found out the PPA responded to the first two conditions and not to the latter. These and other findings motivated the claim that the PPA is specialized for analyzing boundaries of global scenes and hypothesized this effect to be at the basis of children’s use of geometry for navigation (Park et al. 2011; Ferrara & Park 2016).

More recent studies reported activity both in the PPA and RSC (retrosplenial cortex), but not in early visual areas like V1, as related to the passive viewing of boundaries (Epstein 2008; Ferrara & Park 2016). Moreover, the temporary perturbation of the OPA through trans-cranial magnetic stimulation has been shown to result in the selective impairment of boundary-based navigation (Julian et al. 2016), suggesting that the neural mechanisms underlying visual scene perception are not only correlated with navigation, but that they are causally involved in spatial mapping.

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[4] PPA= Parahippocampal place area. RSC= Retro-splenial cortex. OPA=Occipito-parietal sulcus.

5. Defining the perception and function of boundaries: experiments with children

So far, we have discussed the importance of boundaries for navigation across species and how the sensitivity to boundaries is represented across multiple areas of the brain. But what is a definite boundary? How does it distinguish itself from other cues? Although many researchers have discussed the possibility of a "core set" of properties that define a navigational boundary (Kosslyn, Pick & Fariello 1974; Lever et al. 2009; Mou & Zou 2013; Newcombe & Liben 1982), it is not yet clear what a boundary is and how it is perceived. What are the core set of properties that define navigational boundaries? How does their conceptualization change over development?

Behavioral studies with young children have started to investigate these issues by altering the properties of the traditionally used rectangular enclosure (Hermer & Spelke, 1994, 1996), by either modifying the size or height of the walls, their dimensionality (i.e. 2D vs. 3D), their connectedness, their rectilinearity, their luminance and their functionality as obstacles to locomotion (Ferrara & Landau 2015; Lee & Spelke 2008, 2010a, 2011; Lee, Sovrano & Spelke 2012; Lee et al. 2013). For example, Lee & Spelke (2008) tested children with both 90 cm high and 30 cm high boundaries and showed that children succeeded in both conditions. They also showed children failed when the rectangular configuration was made up of four columns or a rectangular cable taped on the floor. In successive experiments, Lee et al. (2011) manipulated the limits of boundaries' representation even further and tested children's ability of using subtle boundaries made up of tiny 2X2 cm roads or two natural bumps protruding on the floor, versus four stark bright columns connected by a suspended cable to prevent movement and a bright rectangular mat. They showed that children succeeded in using the roads and the bumps while they didn't succeed in using the rectangular array of columns as well as with the mat.

Lee and Spelke (2010a) also investigated the functional relevance of size and stability for reorientation and showed that children are able to correctly reorient according to the layout produced by two large 3D columns place against the walls of a room, even when the columns were movable and thus, potentially unreliable. In contrast, children failed when the columns were replaced with flat 2D strips (of the same size and color as the columns) or detached from the walls (such that they were freestanding objects). From these studies the authors concluded that the core set of essential properties for basic representation of boundaries was not strictly determined by their salience and stability (Newcombe & Lieben 1982; Newcombe & Ratliff 2007), but rather by the perceptual properties of extended, 3D structures.

While the studies mentioned above were relevant for starting to define the set of properties boundaries should present in order to be valid input for navigation (namely they established boundaries must be 3D structures, extended on the ground plane), they left room for further questions on the nature of boundaries. In particular in our studies we addressed the role of visual vs. physical barriers (Chapter 1) and the perception of continuous boundary surfaces (Chapter 2) over development by testing children with a transparent array and an array made up of objects, respectively.

6. Boundaries and Euclidean geometry in reorientation and map tasks

In the General Introduction (Section 2 and 3, in particular), we discussed the importance of boundaries for navigation in animals, human adults and children. Although most of the reorientation studies we described above tested children in rectangular environments, children were shown to be also sensitive to the geometry of triangular (Lourenco & Huttenlocher 2006, Huttenlocher et al. 2008), rhombic (Hupbach & Nadel 2005) and octagonal (Newcombe et al. 2010) enclosures. Which components do children use to solve the reorientation tasks in the arrays we spoke of above? Is this geometric analysis specific to the task of navigation?

Euclidean geometry is based on distinct components, which can be also seen in external, navigable environments; namely angle (the relative orientations of two surfaces or edges with respect to one another), distance (the displacement of a surface or object from other objects or from one's current station point), length (the lengths of individual surfaces or objects) and direction (the relative position of surfaces or edges with respect to one another and the size of the corner that they form when conjoined). In all connected polygonal arrays, the different geometric properties of the borders were simultaneously available, making it difficult to establish which ones children used in order to solve the tasks. For example, in rectangular environments, children might have used either their distance from the borders (or the relative distance between the two couples of borders), or the length of the walls in order to solve the reorientation task. Similarly, in rhombic environments, they might be able to either use the difference in amplitude of the angles or their relative distance from the angles themselves.

In 2012 Lee and Spelke conducted a study in which they tested the use of angle, distance, length and direction in children from 24 to 37 months old. They tested children in a reorientation task with fragmented arrays, resembling either a rhombic, a rectangular or a square shape, in order to be able to isolate the different geometric components. In this study they showed that children were able to use distance and direction (both distance and direction of surfaces with respect with one another and their distance and direction with respect of the child's position at the center of the array), but not angle and length.

Yousif and Lourenco (2017) proposed a challenge to such a conclusion (children's exclusive ability to use distance but not angle and length) by claiming that children didn't succeed in the length condition because they amodally completed the arrays used in Lee and Spelke's (2012) experiment. Indeed, in that study, Lee and Spelke used an array in which the four segmented borders had different lengths but were arranged in a squared fashion, while in the distance condition they used four borders of equal length, but arranged in a rectangular fashion. Yousif and Lourenco hypothesized children couldn't use the square shaped array, even if provided with a visible length difference between its borders, to reorient because they tended to perceive and reorient according to the global shape of the array due to a mechanism of completion (i.e. the tendency to perceive the segmented borders as if they were continuous), thereby neglecting the length difference. In order to address this issue, they tested children with four panels of different lengths, at which extremities they put perpendicular panels in order to prevent children from activating a completion mechanism. They showed children were able to use length to reorient in this particular condition. Although Yousif and Lourenco's characterization of children's representation of segmented arrays cannot explain the failures to amodally complete segmented corners, there is a simple empirical way to resolve this question: in our experiment, we isolated the distance and length conditions by using a two parallel borders' array that provides no global polygonal shape.

Another interesting aspect of navigational geometric representation is the fact that children's inability to use angle and length in the reorientation task is in contrast with their capacity of using them in visual form analysis and object perception. A wide stream of research, implementing multiple different tasks, showed that children and infants can also perceive the length and angular relationships that specify the shapes of objects and 2D forms (Schwartz & Day 1979; Gentner 1978; Landau, Smith & Jones 1988; Smith 2009; Pierroutsakos & Deloache 2003). In contrast they showed not to be able to perceive distance and directional information in 2D forms (Lourenco, Huttenlocher & Fabian, 2005). Such a discrepancy between navigation and visual form analysis data led researchers to hypothesize that there are two distinctive mechanisms of geometrical analysis operating behind such capacities (Spelke, Lee & Izard, 2010). One system encodes distance and direction of 3D large scale spaces and one system encodes angle and length properties of small scale visual forms.

Map placement and map reading tasks are very interesting tools to investigate the use of these properties, because in these tasks children must match 2D visual form geometric information with the geometric characteristics of the 3D environment. They thus require the integration of two different analyses; the analysis of the geometric relations between the borders of the navigable space and the visual form analysis on a bi-dimensional small-scale representation. Previous studies on the use of maps in children used either triangular (Whinkler-Roads 2013; Shusterman, Lee & Spelke 2008) or L shaped arrays. By using triangular arrays, the conditions of distance and angle were mixed and both available at once, making it difficult to understand which properties children employed to solve the task. Similarly, L-shape arrays simultaneously presented a difference in length, distance and angle.

In our study (Chapter 3) we carefully isolated the geometric properties of distance and length and tested 30 to 42 month-old children with two freestanding parallel boundaries that differed in either length or distance. Children were tested both in a reorientation task and in a map placement task.

7. A Summary of the Present Thesis

Chapter 1

Navigation by geometric boundaries has been widely documented both in animals and humans (both adults and children), but what defines a surface as a boundary has yet to be determined. In particular, boundaries can be either conceived as physical or visual obstacles. Previous studies have confounded the two properties of boundaries by testing children with boundaries that constituted both physical and visual obstacles. Are children equally sensitive to boundaries that constitute physical or visual obstacles? How does it change over development? In our first study (Chapter 1) we decoupled the two properties by testing children from 2 to 7 years old in a reorientation task with either transparent or opaque surfaces. In Condition 1, children were tested with boundaries made up of transparent surfaces that minimized the visual obstacles, but were still functional as physical obstacles and in Condition 2 children were tested with opaque surfaces that worked as both physical and visual obstacles. We found out that while children were able to use opaque surfaces at any age, they started to use transparent surfaces only from the age of five.

Chapter 2

While children were shown to be able to use 3D extended surfaces, even if segmented into 100 or 80 cm long walls, they were shown to fail the reorientation task when boundaries were made up of single discrete objects. Children were shown to fail both when four objects, even if very bright and stark, were arranged in a rectangular fashion and when three identical objects were organized into a triangular fashion. Nonetheless, based on these studies, it not clear whether children failed in using these kind of boundaries because the objects' configuration was not sufficiently dense to visually underline the geometric shape, or because the boundaries didn't work as physical obstacles. Indeed, it is not clear yet how the functionality of boundaries relates to their capacity of preventing movement and how the boundaries' continuity and length affect navigation. In our study, we tested children with a configuration of 20 objects arranged in a rectangular fashion, such that the objects were sufficiently dense to both prevent movement and to clearly visually underline the geometric structure. In Experiment 1, the objects forming a rectangular configuration were spaced either 16 cm or 8 cm apart. While in Experiment 2 objects were closely aligned as to form either four 50 cm long walls, or two 100 cm long walls. We found out that children start to use the configuration of objects of Experiment 1 from the age of seven, while they are able to use the continuous configurations of objects at any age.

Chapter 3

The literature shows children from as early as the age of two are able to use the geometry of boundaries to orient, not only when tested with rectangular shapes but also with other geometric shapes. But these studies didn't clarify which geometric properties the children use to solve the reorientation task. In particular, it would be interesting to know whether children solved the task basing on the difference in distance between the borders or on the difference in length. Previous studies have made a difference between the use of geometric properties in large-scale and small-scale environments; they have shown that children can use distance and direction, but not length in navigation tasks, while they are able to use length in visual form analysis tasks but not direction. In order to investigate which geometric properties are children most sensitive to, also map studies are particularly interesting, since they require the children to identify and put in relationship the geometric properties of the 3D navigable space with the geometric properties of its small-scale representation. Previous studies with maps showed that 2 year-old children can use angle, length and distance information to solve a map placement task. However, the majority of both reorientation and map studies were limited because they presented the geometric properties of distance, length and angle together, making it difficult to understand whether children used one or the other in order to solve the task. In our study, we started to investigate which geometric components children are most sensitive to by carefully isolating the two properties of distance and length. We tested 32 children (2.5 to 3.5 years old) both on reorientation and map tasks. Our results confirmed that children are able to use distance but not length in a reorientation task from 30 to 42 months old. In contrast, they were not to be able to use distance or length in a map-placement task.

Chapter 1

The developing role of transparent surfaces in children's spatial representation*

***This paper has already been published in a peer-reviewed journal*:** Gianni, E., De Zorzi, L., & Lee, S. A. (2018). The developing role of transparent surfaces in children's spatial representation. *Cognitive Psychology*, *105*, 39

Abstract

Children adeptly use environmental boundaries to navigate. But how do they represent surfaces as boundaries, and how does this change over development? To investigate the effects of boundaries as visual and physical barriers, we tested spatial reorientation in 160 children (2-7 year-olds) in a transparent rectangular arena (Condition 1). In contrast with their consistent success using opaque surfaces (Condition 2), children only succeeded at using transparent surfaces at 5-7 years of age. These results suggest a critical role of visually opaque barriers for spatial coding in early development and a developmental change around the age of five in representing locations with respect to transparent surfaces. In application, these findings may inform our usage of windows and glass surfaces in designing and building environments occupied by young children.

1. Introduction

1. The Developing Role of Transparent Surfaces in Children's Spatial Representation

Decades of research have established that both humans and nonhuman animals can navigate by allocentric representations of the environment that allow them to rapidly map novel environments and to navigate through familiar ones (Burgess, 2008; O'Keefe & Nadel, 1978; Tolman, 1948). How the brain produces these kinds of representations is a topic of wide scientific interest, with investigations implementing a wide range of research methodologies (Derdikman & Moser, 2010, for review). There is converging evidence from behavioral, developmental, neuroimaging, and neurophysiological studies that our hippocampal "cognitive map" computes locations, at least in part, by encoding distances and directions from environmental boundaries and that this representation emerges in the earliest stages of development (Bjerknes, Moser & Moser 2014; Hartley & Lever 2014; Hartley, Lever, Burgess, & O'Keefe, 2014; Lee, 2017; Mayer, Bhushan, Vallortigara & Lee, 2017).

The first behavioral demonstration of boundary-dependent navigation behavior was reported by Ken Cheng in 1986. The researcher showed that disoriented rats, who previously learned the location of a hidden reward within a rectangular arena tended to search for the reward in accord with the geometric shape of the arena. Indeed, they oriented their search by exploring the correct and its opposite diagonal corner (geometrically equivalent) with the same frequency (see Figure 1 for an illustration of what we mean by "correct" and "geometric equivalent" corners) - despite the presence of other visual and olfactory cues (Cheng, 1986). Sensitivity to geometric boundary structure in navigation has since then been observed across many distantly related species - from fishes, to chicks, to monkeys, to humans - indicative of its fundamental nature (Cheng & Newcombe, 2005 for review).

This ability emerges early in development and without any explicit training; for instance, when disoriented in a rectangular room, human toddlers (from 18 months old) tend to limit their searches to the two geometrically correct corners (Hemer & Spelke, 1994, 1996; Lew, Foster, Bremner, Slavin & Green, 2005; Wang, Hermer & Spelke, 1999). Although, depending on their developmental age and depending on the specific situation, children's use of non-boundary features improves significantly (see Cheng & Newcombe, 2005, for review), and the use of boundary layout is found consistently across studies (Lee, 2017). Therefore, while there has been substantial debate amongst developmental psychologists regarding the degree of domain specificity of the mental processes underlying boundary-dependent navigation, there is nevertheless widespread agreement that boundaries play an important role in human spatial cognition from an early age (Cheng, 2008; Cheng, Huttenlocher &, Newcombe 2013; Cheng &, Newcombe 2005; Lee, 2017; Lee & Spelke 2010b; Lew 2011; Newcombe, Ratliff, Shallcross & Twyman, 2010; Twyman & Newcombe 2010). The use of boundaries for navigation has been hypothesized to provide an adaptive advantage (Gallistel, 1990) because the 3D structure of the terrain is a reliable, stable property of the environment across seasonal changes and across time. Furthermore, boundary representation has been argued to be computationally advantageous in that large, extended surfaces can be represented with just a few points each (Gee, Chekhlov, Calway, & Mayol-Cuevas, 2008; Silveira, Malis, & Rives, 2008).

Neurophysiological and neuroimaging studies in both humans and nonhuman animals complement behavioral evidence by offering insight into the neural mechanisms underlying boundary-dependent spatial navigation. Place cells in the hippocampus of vertebrates are especially sensitive to the metric information provided by environmental boundaries and receive major input from boundary cells (in the entorhinal cortex and subiculum) that respond to wall-like surfaces in the testing arena (Hartley, Burgess, Lever, Cacucci, & O'Keefe, 2000; Lever, Jeewajee, Burton, O'Keefe, & Burgess, 2009; Lever, Wills, Cacucci, Burgess, & O'Keefe, 2002; O'Keefe & Burgess, 1996; Solstad, Boccara, Kropff, Moser & Moser, 2008). These mechanisms for coding boundaries are likely to receive inputs from neural circuits mediating the analysis of visual scenes (Epstein, 2005, 2008; Epstein & Kanwisher, 1998), particularly in animals that rely highly on vision. For instance, in nonhuman primates, the entorhinal cortex has been shown to house neurons that fire when the animal looks at the boundaries of visual scenes (Killian, Jutras, & Buffalo, 2012). In humans, the neural correlates of boundary-based spatial representation are not only seen in the hippocampal formation (Bird, Capponi, King, Doeller & Burgess, 2010; Doeller, King & Burgess, 2008; Lee, 2017), but also in visual scene-processing areas such as the Parahippocampal Place Area (PPA), the retrosplenial cortex (RSC) and the Occipital Place Area (OPA, also known as the transverse occipital sulcus, or TOS) (Dilks, Julian, Paunov & Kanwisher, 2013; Epstein & Kanwisher, 1998; Ferrara & Park, 2016;

Greene & Oliva, 2009; Grill-Spektor, 2003; Maguire, 2001; Park, Brady, Greene & Oliva, 2011; Torralba, Oliva, Castelhano & Henderson, 2006).

Although researchers have investigated various possible ways in which a boundary might be defined (Kosslyn, Pick & Fariello, 1974; Lever et al., 2009; Mou & Zou, 2013; Newcombe & Liben, 1982), it is not yet clear what properties characterize navigational boundaries and whether they depend on the functional role of boundary surfaces as visual or physical barriers. Behavioral studies with young children have investigated this issue by altering the properties of the rectangular enclosure traditionally used in reorientation tasks (e.g., Hermer & Spelke, 1994), by modifying the height of the walls, their dimensionality (i.e. 2D vs. 3D), their connectedness, their rectilinearity, their luminance and their functionality as obstacles to locomotion (Ferrara & Landau, 2015; Lee & Spelke, 2008, 2010a, 2011; Lee, Sovrano & Spelke, 2012a; Lee, Vallortigara, Spelke & Sovrano, 2013).

Lee and Spelke (2008) showed that 4 year old children succeeded (success in this task refers to a significantly higher proportion of "correct" and "geometric equivalent" corners' choices over the other two corners) in reorienting by the geometric shape of an array of wall-like surfaces when their height was either 90 cm (that children could see over into a circular room around them) or 30 cm (which children could both see and step over). In a following study, the authors tested the limits of boundary representations even further by demonstrating that young children (4-year-olds) can also successfully navigate by subtle, more-naturalistic 3D terrain structures, such as a rectangular array of wooden rods laid on the ground (2.5 cm in height) or curved speed-bump-like hills protruding from the floor (Lee & Spelke, 2011). In contrast to their proficiency in navigation by such 3D, continuous terrain structures, children performed at chance level when reorienting by a visually salient 2D (flat) rectangular mat or with discontinuous objects such as an array of four tall, free-standing columns marking the vertices of a "virtual" rectangular array. Importantly, children failed to use columns even when the columns were connected by a string that functionally restricted one's movement outside of the array. Lee and Spelke (2010a) investigated the functional relevance of a 3D structure's size and stability and showed that children were able to correctly reorient according to the layout produced by two large 3D columns placed against the walls of a room, even when the columns were movable, and thus, potentially unreliable (success with peripherally placed landmarks was also found previously in Garrad-Cole, Lew, Bremner & Whitaker, 2001; Lew, Gibbon, Murphy & Gavin Bremner 2010). In contrast, children failed when the columns were replaced with flat 2D strips (of the same size and color as the columns) or when the columns were detached from the walls, such that they were freestanding objects.

These studies suggest that the essential properties for basic representation of boundaries were not strictly determined by their salience, stability, and experienced reliability (Newcombe & Lieben, 1982; Ratliff & Newcombe 2008), but perhaps rather by the perceptual properties of surfaces that make up the continuous, 3D geometric structure of the environment. Although past experiments demonstrated that children do not require large barriers to use them to code location, none of them directly addressed whether 3D boundaries were represented according to their function as barriers to visual analysis or physical movement. Because under normal circumstances (in which surfaces block visual access) visual and physical function of 3D boundaries are confounded, all of the 3D boundary structures in previous studies provided children both with surfaces that were opaque barriers to vision (even when short in height) and with surfaces that were physical obstacles to movement (even when subtle and easy to overcome). Given these findings, what role does visual opaqueness of surfaces play in their effectiveness in spatial navigation?

1.1 Visual Boundary Representation in Navigation

Visual estimation of metric properties such as distance from the boundary structure have a powerful influence on spatial navigation in both human toddlers (Huttenlocher & Lourenco, 2007; Lee, Winkler-Rhoades & Spelke, 2012b; Lourenco, Addy, & Huttenlocher, 2009) and nonhuman animals (Lee et al., 2013; Twyman, Newcombe, & Gould, 2009). For instance, in one study human toddlers distinguished the corners of a squared shaped arena when its walls were covered with small and large visual dot patterns on opposing pairs of walls (Huttenlocher & Lourenco, 2007), but only when they were arranged such that they could significantly alter the visual perception of depth and distance (Lee et al. 2012b). This may also explain why an arena with two opposing pairs of walls of light gray and of dark gray allow toddlers to discriminate the corners, while two red and two blue walls do not (Huttenlocher & Lourenco 2007; Lourenco et al. 2009).

Studies on the neural correlates of visual boundary perception in human adults suggest that even without active navigation, high-level visual processing areas of the brain like the PPA, OPA and RSC are actively engaged in analyzing the global visual surface structure of the environment (Epstein, 2005, 2008; Epstein & Kanwisher, 1998; Park, Brady, Greene & Oliva, 2011; Park & Chun, 2009). Recent studies reported that activity in the PPA (but not in early visual areas like V1) distinguishes scenes with 2D rectangular mat-like forms from similar scenes with small curb-like boundary structures (Ferrara & Park, 2016). Interestingly, these effects disappeared when the scenes were inverted, suggesting that the visual analysis of boundaries is specific to surfaces extending from the ground plane for navigation. Recent studies suggest that these visual-processing areas of the brain are also activated in virtual navigation tasks, selectively responding to conditions with extended boundaries as opposed to pillars or 2D flat-mat configurations (Sutton, Twyman, Joanisse &

Newcombe, 2012). Moreover, the temporary perturbation of the OPA through transcranial magnetic stimulation has been shown to result in the selective impairment of boundary-dependent navigation (Julian, Ryan, Hamilton, & Epstein, 2016), suggesting that the neural mechanisms underlying visual scene perception are causally involved in spatial navigation.

Navigational and visual processes appear to be deeply intertwined and both engaged in our cognitive representation of spatial relationships, naturally raising questions about the role of visual boundary representations in navigation. The boundaries in visual scenes are usually barriers (i.e., opaque surfaces) that occlude the part of the scene that is behind them. And yet, in rats, at least, the role of boundaries as functional obstacles to physical movement may be crucial for them to be represented by spatially selective neurons. In particular, boundary cells in the rat hippocampal formation (Stewart, Jeewajee, Wills, Burgess, & Lever, 2014) respond to both cliff-like drops and upright wall-like boundaries. What is the interaction between visual and physical information in boundary-based navigation? As adults, we expertly maneuver ourselves around with respect to windows and glass doors without ever mistaking such areas as being unbounded space (most of the time). However, young children's representation of transparent boundaries may be different from ours, despite their experience in a world full of transparent surfaces. And children's representation of transparent surfaces may change over development and accumulated experience with physical barriers that they can see through. The present study aims to address these questions in children from 2 to 7 years of age by testing children's spatial navigation in arenas consisting of transparent (Condition 1) and opaque surfaces (Condition 2), as well as children's understanding of transparent surfaces as solid objects (Control Tests).

1.2 The Present Study

Children, from an early age, are highly dependent on continuous, 3D boundaries in spatial mapping tasks (toddlers in navigation: e.g., Hermer & Spelke, 1994, 1996; infants in visual exploration: e.g., Lew et al., 2005), even when their size, stability, and visual contrast are considerably decreased (Lee & Spelke, 2008; 2010a,b; 2011, Lee et al., 2012a,b). But even those subtle boundaries still provide subjects with both visually and physically obstructive cues. Are young children's representations of boundaries based on surfaces that only obstruct action (Condition 1), or both vision and action (Condition 2)? Does that representation change over development?

In the present study, we tested 2-7-year-old children's navigation within an arena made of transparent walls that preserve the tactile, physical structure of boundaries but minimize their function as visual barriers or visual scene elements (Condition 1). Second, we replicated and expanded upon past studies on boundary-dependent reorientation on a wider age range (Condition 2) by using opaque wall panels that provided both visually and physically occlusive cues. Finally, we investigated whether children are able to perceive the transparent surfaces as solid and impossible to pass through (Barrier Test). We chose to test children on a wide age range in order to maximize our chances in observing developmental changes in spatial ability (e.g., Bullens et al., 2010; Ferrara & Landau, 2015; Gogtay et al. 2006; Hermer-Vazquez, Moffet & Munkholm, 2001; Landau & Lakusta, 2009; Spelke, Lee & Izard, 2010). In particular, we aimed to compare performance with respect to the transitional age of 5 years, at which spatial cognition and navigation has been shown to improve significantly such that the children become able to incorporate spatial information in a more abstract and flexible way (Hermer-Vazquez et al. 2001; Park, Ferrara, Landau 2015).

2. Method

2.1 Participants

Participants were 160 healthy children ranging from 22 to 95 months of age who were recruited from daycares and recreational centers in and around Rovereto, Italy. They were sampled independently of their demographic or socio-economic characteristics. Subjects were randomly split between Conditions 1 and 2 with a balanced number of males and females: 48 children, 25 boys and 23 girls were tested in Condition 1, and an equal number of children, 27 boys and 21 girls, were tested in Condition 2. Participants were divided into two age groups: 2-4 years old and 5-7 years old. In Condition 1 (transparent condition), we had 40 subjects in the younger group (24 to 59 months, *Mean*=41.1, *SD*=10.6: 13 2-year-olds, 14 3-year-olds, 13 4-year-olds) and 40 subjects in the older group (60 to 92 months, *Mean*=77, *SD*=9.4: 14 5-year-olds, 14 6-year-olds, 12 7-year-olds). Similarly, in Condition 2 (opaque condition), we had 40 subjects in the younger group (22 to 59 months *Mean*=41.8, *SD*=11.6: 13 2-year-olds, 14 3-year-olds, 13 4-year-olds) and 40 subjects in the older group (60 to 95 months, *Mean*=76.9, *SD*=11.3: 15 5-year-olds, 14 6-year-olds, 11 7-year-olds). The participants visited the laboratory accompanied by an adult, usually a parent. At the end of the test each child was given a certificate of participation and a souvenir (usually a small toy). 19 additional participants (9 in Condition 1 and 10 in Condition 2) either refused to participate entirely or failed to complete the entire test (four trials) and were omitted from the data analysis. Informed consent from the parent or guardian and verbal consent from the child were obtained prior to the study.

2.2 Experimental Setting

Experiments were conducted within a windowless, soundproof room of the laboratory. Black curtains hanging from a circular track formed a cylindrical enclosure (2.1 m diameter, Figure 1). The side of the enclosure facing the room's door had an opening that served as the entrance, and the floor was a uniform light-grey color. Once closed, the opening was made invisible (by accurately closing the circular curtain) in order not to provide any external cue. At the center of the enclosure was the experimental arena (160 cm by 100 cm rectangular arena, 40 cm in height, with a plain white, inverted cup in each corner - see Figure 2a-b). The experiment was recorded through a hidden video camera hanging from the center of the ceiling of the testing room. A second experimenter watched and recorded the behavior from an adjacent room through a video projection of the experiment.

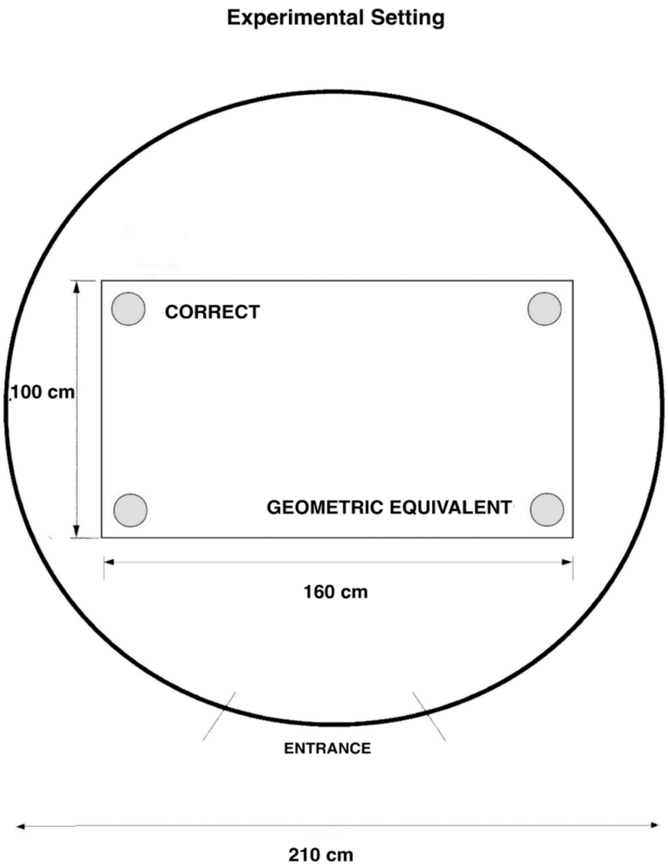


Figure 1. Experimental setting, schematic view from above. If the sticker was placed in the northwest corner (labeled "correct"), the diagonally opposite southeast corner (labeled "geometric equivalent") is indistinguishable from the correct corner for disoriented subjects. Therefore, a proportion of correct + geometric equivalent responses that exceeds chance level indicates successful encoding of boundary structure.

2.3 Design

Children were tested on four separate trials with the target position in the same location and motivated by rewarding them with stickers. The target position was kept the same in order for the children not to get confused across trials. We chose this version of the task, as opposed to a version where the goal position changes across trials (Hermer-Vazquez, Spelke & Katsnelson 1999), based on previous reorientation studies (Hermer & Spelke 1994; Lee & Spelke 2008, 2010a, 2011) in order to avoid memory interference from previous trials. These studies (as well as our study - see results section) showed there was no effect of training across trials. Equal numbers of children were tested with each corner as the target. The direction in which children faced at the end of the disorientation procedure (one of the four walls of the rectangular arena) was varied across trials and counterbalanced across participants.

To assess the use of the spatial information provided by the environmental layout, the total proportion of correct and geometrically correct first choices was computed for each subject. Scores were averaged across subjects for every age group. A univariate ANOVA was used to compare between-subjects variables (age group, condition) across the two conditions. Independent-sample t-tests (both parametric and non-parametric) were used to compare across age groups in each condition.

2.4 Experimental Procedure

Upon arriving at the laboratory, children first spent some time in the play-area where they had the chance to get comfortable with the setting and the experimenter. After about 10 minutes of playing, the experimenter accompanied the children into the testing room and taught them about the rules of the "sticker-finding game." If the children agreed, the parents watched the experiment in an adjacent room with the second experimenter, from a screen connected to the video camera. The experimenter asked the children to choose both the stickers and the style of blindfold they preferred to use. The experimenter then stepped over the wall, into the arena with the children, helping them if they could not step over it by themselves. Each trial started with hiding a sticker under a cup in the target corner. The children then put on a blindfold and turned around in place slowly for about 10 seconds. The experimenter then guided the children to the center of the arena, stood behind them, removed the blindfold and encouraged them to search for the sticker. If the first search attempt was not correct the experimenter revealed the correct location. The procedure was repeated for 4 trials. To provide motivation, the children were rewarded with a sticker every time they found it. If children refused to participate without the presence of their parent, the parent was allowed to enter the experimental room. Parents were instructed to stand outside the arena and, when children were rotated, to silently walk around the arena to a position that was previously pointed out by the experimenter. This ensured that the parent was positioned behind the children (out of their view) when the blindfold was removed. In some cases, when children were particularly shy, testing took place with parents holding them in their arms. In this case the experimenter rotated both parents and children, taking care to have parents stand directly behind the children (and looking down) when the blindfold was removed. Out of 80 subjects in the younger group (2-4-yearolds), one subject was tested with the parent present in the testing room and four subjects were tested with parents holding them in their arms. By analyzing the results, we ensured these subjects did not perform differently from the others. All experiments were approved by the Ethical Committee of the University of Trento and conducted in accordance with the institutional guidelines for human subject testing.

3. Experiment

In our experiment we tested an equal number of children (See section 2.1) in two different conditions. In Condition 1 we investigated children's spatial reorientation within a minimally visually obstructive rectangular environment made of Plexiglas surfaces (160 cm x 100 cm x 40 cm) (Figure 2a). In Condition 2, we tested children's spatial reorientation within the same rectangular environment made up of opaque surfaces (Figure 2b). In previous studies, toddlers successfully navigated with respect to environmental geometry in a fully-enclosed rectangular room (Hermer & Spelke 1994; Learmonth, Newcombe & Huttenlocher 2001), as well as in a circular arena with four freestanding walls of equal length arranged in a rectangular formation (Lee et al, 2012a). In Condition 2, opaque white panels (80 cm) were attached to the center of each wall of the transparent arena (from Condition 1), providing the children with boundaries as both visual and physical obstacles (Figure 2b). We chose to use extended opaque panels (as in Lee et al. 2012a, instead of fully continuous walls as in Hermer & Spelke 1994, 1996) in combination with the transparent arena in order to keep the corner goal locations (the cup surrounded by the corner of the transparent acrylic structure) and the size of physically navigable space identical to Condition 1.

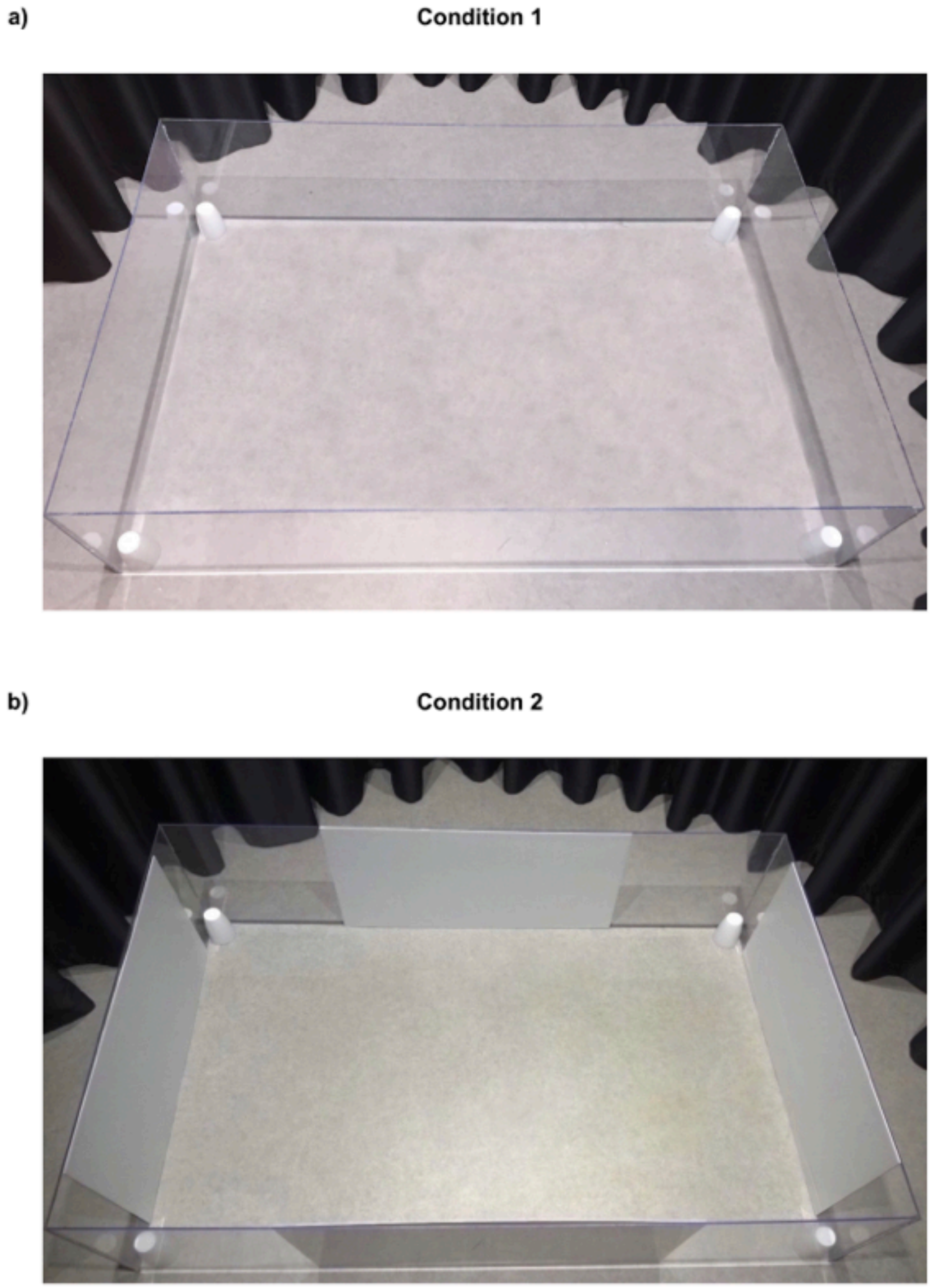


Figure 2. a) Condition 1: experimental apparatus with transparent surfaces. b) Condition 2: experimental apparatus with opaque surfaces.

3.1 Overall Results.

In order to compare across the two conditions, we conducted a univariate ANOVA with the proportion of geometrically correct choices as the dependent variable and age group (2-4 years, 5-7 years) and condition (transparent, opaque) as between-subjects variables. We found a significant effect of group ($F(1,156) = 7.84$, $p=0.006$, eta-squared = 0.048), indicating that older children were better than younger ones; a significant effect of condition ($F(1,156) = 5.45$, $p = 0.021$, eta-squared = 0.034), indicating better performance in the opaque condition; and a significant interaction of group by condition ($F(1,156) = 4.09$, $p = 0.045$, eta-squared = 0.026), reflecting the presence of an age effect only in the transparent condition and not in the opaque condition. This interaction was further investigated using post-hoc pair-wise t-tests. They confirmed that there was a significant difference between the groups 2-4-year-olds and 5-7-year-olds in the transparent condition $t(78)=3.31$, $p=0.001$; but not in the opaque condition $t(78)=0.56$, $p=0.572$ (Figure 4). Furthermore a significant performance difference was found between the two conditions for children in the ages 2-4, $t(78)=2.96$, $p=0.004$, but not for children in the ages 5-7, $t(78)=0.22$, $p=0.819$ (Figure 3).

Figure 4c, which plots performance by age in years, suggests a sudden developmental change in the transparent condition around the age of 5 that is not present in the opaque condition. Two tailed t-tests against the level of chance for the transparent condition (Condition 1, Figure 4a) and the opaque condition (Condition 2, Figure 4b) are shown for each age.

In order to further explore the age effects, the data were broken down into 6 different age groups (2-year-olds, 3-year-olds, 4-year-olds, 5-year-olds, 6-year-olds and 7-year-olds) for both conditions. Univariate ANOVAS with year-group as independent variable and the proportion of geometrically correct searches (correct + geometrically equivalent corners) as the dependent variable were used to explore differences in performance by age in years for the two conditions. They showed a significant effect of year-group for the transparent condition (F=5, 74)=0.92, p=0.03, while the same effect was not significant for the opaque condition (F=5,74)=0.105, p=0.89.

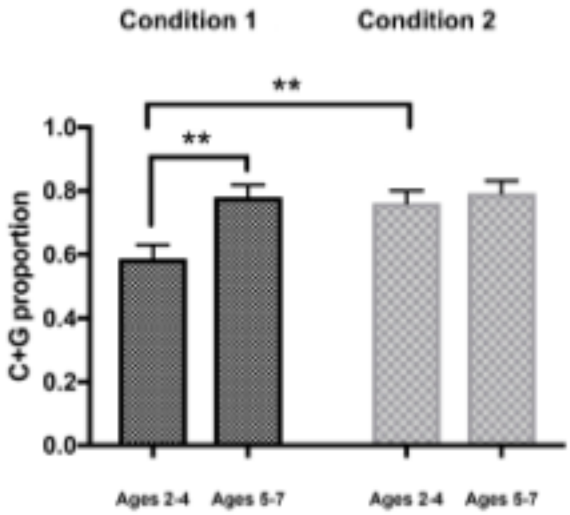


Figure 3. The graph presents the proportion of correct (C) + geometrically equivalent (G) searches averaged across subjects in each age group for Condition 1 (dark grey bars) and Condition 2 (light grey bars). Error bars represent SEM. Independent-sample t-tests assessed differences in children's performance across the age groups and across the two experiments (** represents p< 0.01).

a) CONDITION 1 (TRANSPARENT CONDITION)

YEARS	NUMBER OF SUBJECTS	T-TEST AGAINST 0.5	P-VALUE
2	13	$t(12)=1.10$	$p=0.29$
3	14	$t(13)=1.09$	$p=0.29$
4	13	$t(12)=1.17$	$p=0.26$
5	14	$t(13)=2.74$	$p=0.01$**
6	13	$t(13)=4.83$	$p<0.001$***
7	12	$t(11)=6.51$	$p<0.001$***

b) CONDITION 2 (OPAQUE CONDITION)

YEARS	NUMBER OF SUBJECTS	T-TESTS AGAINST 0.5	P-VALUE
2	13	$t(12)=3.74$	$p=0.003$**
3	14	t(13)=3.60	$p=0.003$**

4	13	$t(12)=4.07$	$p=0.002$**
5	15	$t(14)=4.79$	$p<0.001$***
6	14	$t(13)=3.18$	$p=0.007$**
7	11	$t(10)=5.88$	$p<0.001$***

c)

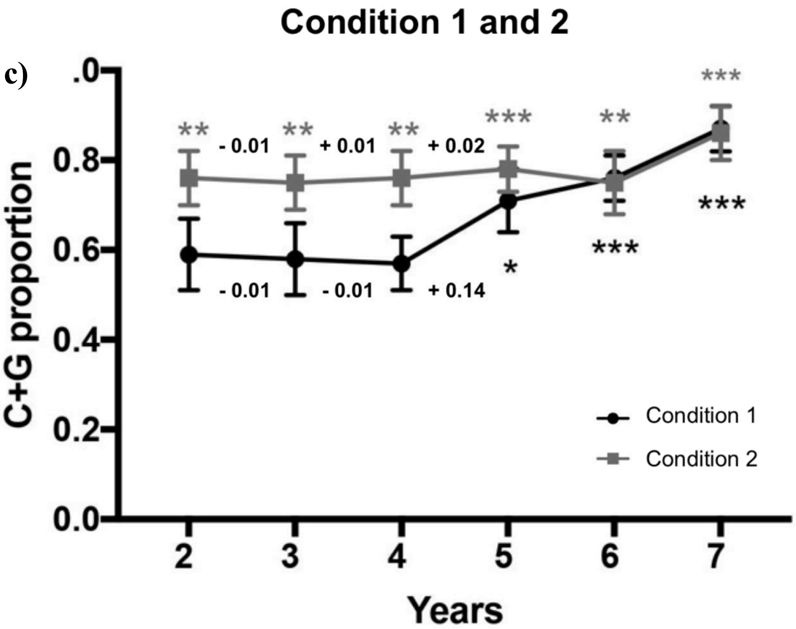


Figure 4. *a)* The table presents the number of subjects, the values of the t-tests against the level of chance and their p-value for Condition 1 (transparent condition. *b)* The table presents the number of subjects, the values of the t-tests against the level of chance and their p-value for Condition 2 (opaque condition). *c)* The graph presents the proportion of correct (C) + geometrically equivalent (G) searches averaged across subjects divided by year-groups for Condition 1 (transparent condition, shown in black) and Condition 2 (opaque condition, shown in gray). Asterisks indicate t-tests against the level of chance (0.5). (* is p< 0.05, ** is p< 0.01, *** is p< 0.001). The numbers below indicate the slopes of the straight lines for Condition 1 (transparent condition) between 2 and 3 years (-0.01), 3 and 4 years (-0.01), and 4 and 5 years (+0.14). The numbers above indicate the slopes of the straight lines for Condition 2 (opaque condition) between 2 and 3 years (-0.01), between 3 and 4 years (+ 0.01) and between 4 and 5 years (+ 0.02). These slopes reflect a steady trend in the transparent condition between 2 and 4 years and a sudden change around 5 years. While in the opaque condition the slope reflects a constant, steady trend between 2, 3, 4 and 5 years.

3.2 Condition 1: Transparent (Minimally Occlusive) Boundaries

In order to provide further details, the analysis was also conducted separately for each condition. For Condition 1, a univariate ANOVA with age group and sex as independent variables and the proportion of geometrically correct searches (correct + geometrically equivalent corners) as the dependent variable was used to compare the difference between the proportion of correct + geometric equivalent choices across the two age groups 2-4 years old (*Mean*=0.58, *SEM*=0.04) and 5-7 years old (*Mean*=0.78, *SEM*=0.03). The ANOVA showed a significant effect of age group ($F(1,76)=9.66$, $p = 0.003$, eta-squared = 0.113) and no effect of sex, ($F(1,76)=0.78$, $p=0.38$, eta-squared = 0.010). Each age group's geometric search proportion was compared against a chance level of 0.5 to reveal that while the 5-7-year-old group performed clearly significantly above the level of chance ($t(39) = 7.37$, $p = 1.3 \times 10^{-8}$, Bonferroni-corrected, Figure 5a), the 2-4-year-old group did not, ($t(39) = 1.97$, $p = 0.11$, Bonferroni-corrected; Figure 5a). Given the discrete nature of the variables under analysis (i.e., in four trials, the geometrically correct searches are not continuous), we confirmed these findings by comparing performance across age groups using non-parametric statistics (Mann-Whitney $U = 494$, $p = 0.002$).

In order to ensure that children were disoriented and were not guided by any cues other than environmental geometry (in which case children would distinguish the correct corner from the rotationally symmetric corner), we compared the proportion of correct and geometrically equivalent searches for each age group. The results showed that children could not distinguish the correct corner from its geometric twin both in the 2-4-year-old group ($t(39) = 1.23$; $p = 0.23$) and in the 5-7-year-old group ($t(39) = 0.78$; $p = 0.43$). Moreover, in order to investigate whether there was an effect of training across the four trials, we conducted a Repeated-measures ANOVA with "Trial" as the within-subjects factor. The ANOVA showed no significant effect of trial ($F(3,237)=1.69$, $p=0.168$), demonstrating that there was no improvement of the performance across trials, even though the goal-corner was kept the same for four trials.

3.3 Condition 2: Opaque Boundaries

For Condition 2, a univariate ANOVA, with group and sex as independent variables and proportion of geometrically correct choices as the dependent variable, was conducted to compare the difference across groups. However, unlike the results of the transparent condition, the two age groups (2-4-year-olds: *Mean* = 0.76, *SEM* = 0.03; 5-7-year-olds: *Mean* = 0.79, *SEM* = 0.03) did not differ in their navigation performance ($F(1,76) = 0.36$, $p = 0.55$, eta-squared=0.005). Additionally, t-tests against the level of chance (0.5) showed that both groups performed significantly well above the level of chance: 2-4 age group, $t(39) = 6.74$; $p = 9.8 \times 10^{-8}$, Bonferroni-corrected; 5-7 age group, $t(39) = 7.55$; $p = 7.6 \times 10^{-9}$, Bonferroni-corrected (Figure 5b). Non-parametric statistics confirmed the parametric comparison between age groups (Mann-Whitney $U = 732$; $p = 0.48$). There were no effects of sex ($F(1,76) = 0.31$, $p = 0.58$, eta-squared=0.004).

To ensure that children were not using uncontrolled cues besides the symmetrical environmental geometry, we compared the proportion of correct and geometrically equivalent searches) and found that children were disoriented and could not distinguish between the two corners: 2-4 age group $t(39) = 0.49$; $p = 0.62$; 5-7 age group $t(39) = 0.46$; $p = 0.64$. As in Condition1, there was no change in performance across trials ($F(3,237)=0.85$, $p=0.463$).

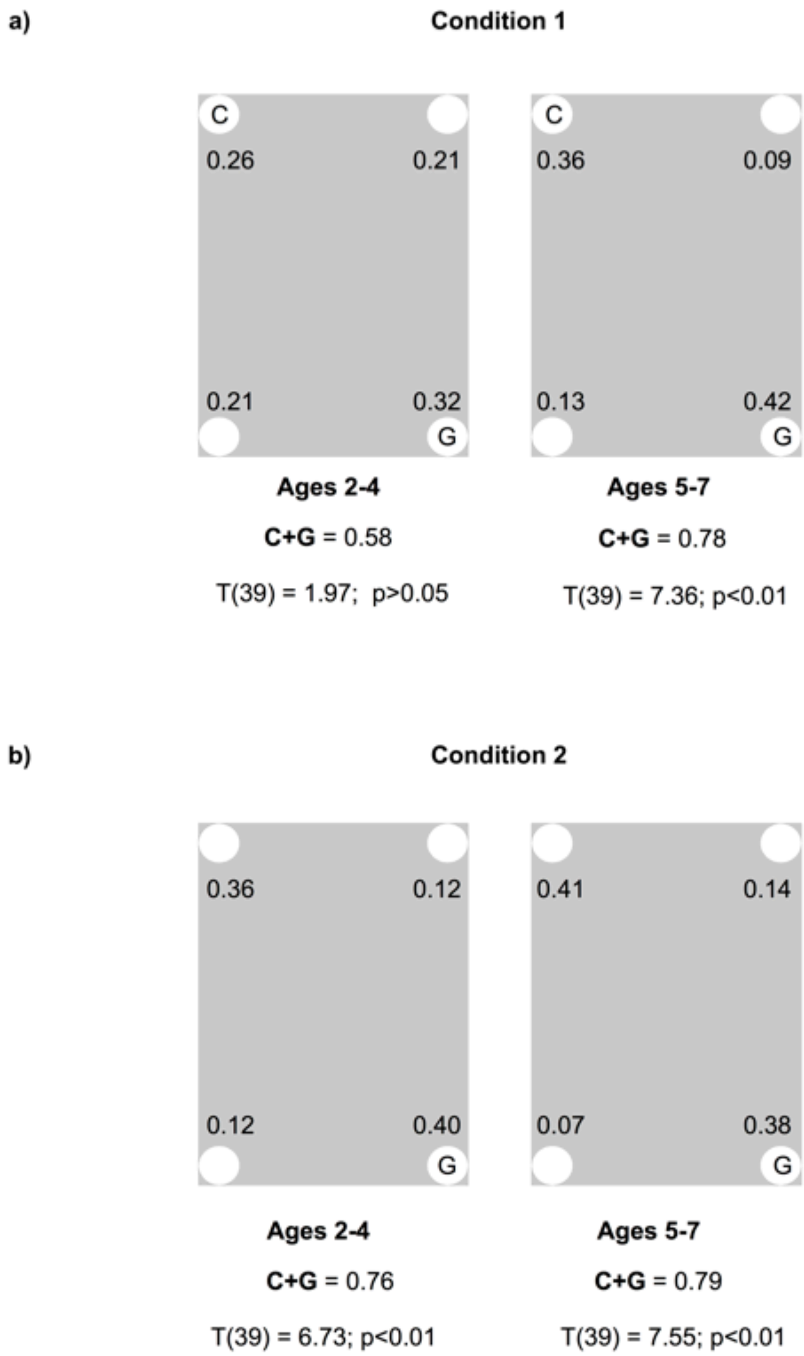


Figure 5. a) Mean percentages of choices, averaged across subjects for each corner in Condition 1. All data rotated to be

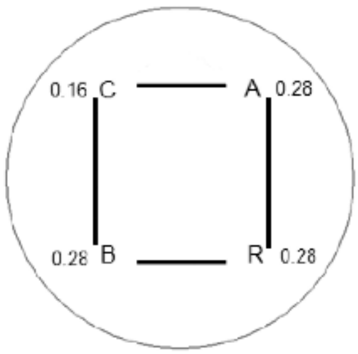
aligned at C. Below that are the proportions of C+G (correct + geometrically equivalent choices) and their t-tests against the level of chance (0.5). b) Mean percentages of choices, averaged across subjects for each corner in Condition 2. All data rotated to be aligned at C. Below that are the proportions of C+G (correct + geometrically equivalent choices) and their t-tests against the level of chance (0.5).

4. Discussion

The findings of Condition 1 reveal that in contrast with past findings using visually-occluding barriers, children are not able to incorporate surfaces that do not provide visual barriers into their spatial representation until the age of 5. The successful performance of the older (5-7-year-old) children indicates that boundary-dependent spatial navigation does not necessarily *require* visual occluding boundaries. On the other hand, the chance performance of the 2-4-year-olds suggests that the absence of visual (occluding) surface structure impairs early navigation.

The results of Condition 2 confirm and extend past findings that young children successfully reorient using an array of segmented boundaries. Although the aspect ratio tested in the present Condition was more difficult than in previous studies (Lee et al., 2012a; Yousif & Lourenco, 2017), children in all age groups succeeded with opaque, visually-occluding panels. Furthermore, we found no significant improvement over development from 2 to 7 years of age in this task.

One alternative interpretation of the success in this condition is that the task could be solved using the boundaries as "landmarks" instead of boundaries, by encoding the correct location as "the cup that is closer to the end of a boundary." Based on several previous studies showing young children's failure to solve a spatial memory task using distance relations from freestanding objects (e.g., Gouteux & Spelke, 2001; Yousif, Lourenco 2017; Lee et al. 2012a-b; Lee & Spelke 2010a; Lee, Shusterman & Spelke 2006; Nardini, Burgess, Breckenridges & Atkinson 2005), we can exclude this hypothesis. In particular, Lee et al. (2012a) tested children in a very similar reorientation task with segmented panels (arranged as in our experiment with respect to the cups) both in a squared and in a



rectangular arrangement; children succeeded only in the rectangular condition and failed when the panels were arranged in a squared shape (which also consisted of target locations that were both closer or farther from the end of the surface, Figure 6). Their failure in reorienting in the squared environment showed children are not able to use panels as polarizing landmarks to solve the task and this conclusion can be extended to our experiment (Condition 2).

Figure 6. Figure from Lee et al. 2012a. Published with permission of the authors. Schematic drawing of the arena used in Experiment 7 by Lee et al 2012a. The panels were arranged in a squared shape. Children failed the reorientation task with this apparatus, even though the panels could be used as landmarks.

5. Control Tests

In the above experiment, none of the subjects bumped into the transparent surfaces, claimed to not see the structure, or described the walls as “soft” or “flimsy.” Nevertheless, it is conceivable that younger children failed in Condition 1 of our experiment because they did not notice them nor understand that they are physical barriers. We conducted two tests in order to rule out this hypothesis. First, a familiarization procedure was performed on a subset of subjects in Condition 1 to provide children with experience with the transparent walls of the arena starting the spatial search task. Additionally, a subset of randomly-selected subjects from both Condition 1 and Condition 2 were recruited for a barrier reaching task following the spatial search task, to test their understanding of the transparent surface as solid obstacles to movement.

5.1 Familiarization Procedure

Prior to starting the experiment in Condition 1, 10 of the children chosen at random from the younger age group (2-4 years old) underwent a familiarization procedure with the testing environment and the apparatus in order to ensure children were aware of the surrounding, transparent surface layout and that they could reliably experience its solidity and consistency. The procedure consisted of three steps: first, the children's attention was directed to the arena by the experimenter who, upon entering the experimental room with the children said, “Look what is this? Wow, it is like a crystal room, isn't it?” The experimenter waited for the children to give a positive answer, in order to ensure they could visually perceive there was a structure in the room. Next, the experimenter invited the children to climb into the arena in order for them to gain a direct experience of its functionality as a barrier, but without giving any suggestion on how to do it. If the children encountered difficulties due to the apparatus' height, the experimenter offered a hand. Third, after positioning the children at the center of the arena, the experimenter invited them to go towards the boundaries from the center, then to touch them along each one of the four walls, asking them to verbally report the way they felt (i.e., hard, smooth). This last step was done to ensure children experience both the solidity and consistency of the material and the four sides of the arena creating a rectangular shape.

Results. To explore the effect of the pre-test familiarization procedure, independent-sample t-tests were used to compare the reorientation task performance (correct + geometrically correct searches) of the 10 subjects who got familiarized (*Mean* = 0.60, *SEM* = 0.08) with the performance of the remaining 30 subjects belonging to the same age range (2-4 years old), (*Mean* = 0.58, *SEM* = 0.05) who did not get the familiarization procedure. The results showed that these two groups did not significantly differ in their performance at the reorientation task, (t (38) = 0.16, p = 0.87, *Cohen's d* = 0.07); this was confirmed using non-parametric analysis methods (*Mann Whitney U* = 148; p = 0.95).

5.2 Barrier Test

In order to conduct an additional test to assess whether younger children correctly understood the functionality of the transparent surfaces as solid and impossible to pass through, ten 2-3-year-old subjects were randomly chosen after they had completed the reorientation task with either transparent (5 children) or opaque surfaces (5 children). They were taken to an adjacent room for a simple, table-top reaching task.

The experimenter placed himself behind a piece of 40cm x 40cm transparent Plexiglas surface of the same type used for the arena walls, which stood fixed to a polystyrene base, with the children sitting on their parents' lap and watching from the other side of the table. On the experimenter's side of the transparent barrier stood 3 white inverted cups. The experimenter hid a sticker under one of them while making sure to get the children's attention. The children were then asked to retrieve the sticker (they could either reach around the side of the transparent structure or reach the toy from above). Children received 3 to 5 trials each (depending on their level of motivation and attention). In order to be as conservative as possible, children were assigned a score of 0 if they ever bumped into the transparent barrier on *any* of the trials and only given a score of 1 if they reached around the barrier on all of the trials.

Results. Of 10 children, one child refused the task. Out of 9 remaining children, only one (26 months old) bumped into the transparent surface on one of the trials of the toy-reaching task. The remaining 8 children correctly solved the task by either reaching around the barrier from the side (4 children) or from above (4 children) (Table 1). A binomial test was used to compare the results against the level of chance probability (0.5) (*Observed proportions* = 0.89, 0.11; p = 0.039).

SUBJECT	MONTHS	CORRECT TRIALS	INCORRECT TRIALS	SCORE
LVAI060212	47	4	0	1
CB110313	35	4	0	1
PF281213	25	4	1	0
BN231013	28	3	0	1
PT301213	27	3	0	1
SM150213	36	5	0	1
FE180213	36	5	0	1
SY190613	41	4	0	1
SA130315	32	4	0	1
LG031214	26	-	-	-
N=10	MEAN=33.3	MEAN=4	MEAN=0.11	TOT=8 out of 9

Table 1. Results of Barrier Test. Children (ranging from 25 to 47 months; mean age in months=33.3), completed from 3 to 5 trials and got a score of either 0 -if they got 1 trial or more incorrectly – or 1 – if they got *all* trials correctly.

6. General Discussion

In this study we set out to gain insight into the role of visually occluding barriers to children's ability to represent space for navigation. We found that, while children remembered spatial locations with respect to opaque boundaries from the age of two, they reliably used transparent boundaries starting around the age of five. Moreover, the powerful effect of boundaries in human navigation is also in line with studies on adult navigation in virtual environments that have shown that 3D boundaries play a special role in navigation but also that their influence is largely independent of their salience or appearance (Doeller & Burgess, 2008; Julian et al., 2016).

On the other hand, the failure of 2-4-year-old children in the task seem, at a first glance, to be in contrast with Lee & Spelke's (2011) findings that young children (aged 3 to 4 years) can use even very subtle boundaries (2.5-cm-high). The difference might lie in the fact that those boundaries still provided children with a sufficient amount of visually fully opaque surfaces to represent the 3D structure of the environmental layout. In our experiment, however, 2-4-year-old children failed with boundaries that were taller in height but devoid of clear visible barriers (i.e., minimally visually obstructive). Our data indeed confirmed that subtle 3D boundaries and transparent boundaries are used differently in navigation.

What explains then the failure of the 2-4-year-olds and the subsequent change around the age of five? First, as shown by the control tests, it is unlikely that young children simply fail to perceive the transparent boundaries or fail to understand that they are solid, physical barriers. A more plausible explanation is that transparent surfaces are a form of visual illusion and that such "unnatural" classes of boundaries are not initially incorporated into a basic spatial representation of the environment. In this view, the success achieved at five years of age can be attributed to an acquired ability to represent space (or spatial boundaries, in this case) in an abstract way. Indeed, the development of abstract knowledge has been implicated in forming spatial representations of higher complexity (e.g., Hermer-Vazquez, Spelke & Katsnelson, 1999; Hyde et al. 2010; Shusterman & Spelke, 2005). However, it is not clear that such high level cognitive abilities are necessary to represent space without visual access to boundaries, particularly given that place cells in the rat are functional (albeit less stable in their representation) even when animals are navigating in the dark (Quirk, Müller & Kubie, 1990) or are blinded at birth (Save, Cressant, Thinus-Blanc & Poucet, 1998) and given that boundary cells respond equally strongly to both tall walls and cliff-like edges (Lever et al., 2009; Stewart et al., 2014).

A possible alternative to the first two explanations is that although younger children can correctly conceive the transparent surface as a physical obstacle, it takes them time to overcome the discrepancy between the visual input that indicates an absence of visually occlusive boundaries and the physical input that indicates the presence of a consistent environmental surface structure. Such a view would explain why younger children need surfaces to both obstruct movement and vision in order to correctly use them for navigation and might predict that younger children's brain function may not be mature enough to process the input that indicates the presence of a physical boundary (provided by the transparent surfaces) independently from the visual stimulus or to inhibit the visual input, indicating an absence of boundaries. On the other hand, children older than 5 years of age may succeed in this task because they have had more experience with the "counter-intuitive" perceptual nature of transparent surfaces (physical but not visual obstacles). These and related ideas may be explored in future studies investigating the interaction between visual processing of scenes and tactile mapping of navigational space, not only in typically developing children but also in congenitally blind children, as well as the development of multi-sensory integration during navigation in children (Burr & Gori 2012; Nardini, Bedford & Mareshal 2010).

Future studies are needed clarify whether the present findings are explained by the heavy contribution of boundary-based visual scene processing or by a domain-specific (whether innate or learned) spatial mapping mechanisms that results in an early inability to cope with a discrepancy in visual and physical information. Understanding the functional specificity of the different areas constituting the visual scene processing network (i.e., PPA, RSC, OPA) (Epstein, 2008; Ferrara & Park, 2016; Epstein & Higgings, 2007; Julian et al., 2016) and their emerging contributions to spatial navigation over development (e.g., Sutton et al., 2012; Golarai et al. 2007) will be particularly relevant for gaining insight into the changing neural representation of perceptual inputs to spatial cognition. For instance, navigation by non-visually-occluding (e.g., transparent) boundaries may be correlated with the development of the RSC, which has been suggested to be more specialized for physical and functional properties of visual scenes (Epstein & Higgings, 2007; Ferrara & Park, 2016).

7. Conclusion

Converging evidence from various fields of cognitive research, from psychology to neurobiology supports the existence of an early-emerging representation of space that relies on environmental cues such as boundaries. The present study makes an important contribution to the understanding of the origins of spatial mapping in humans by showing that young children have difficulty coding spatial locations with respect to transparent boundaries, despite the fact that even 2-year-olds demonstrate a basic understanding of the solidity and functional relevance of transparent surfaces as obstacles to movement.

Visually occlusive boundaries may play an important role in their representation for navigation. By demonstrating that the ability to navigate using opaque surfaces is available earlier in development than surfaces that afford visual access through them, the results of this study are consistent with this hypothesis. Although children eventually overcome these limitations and successfully navigate by transparent boundaries, these results provide us with some insight as to how children conceive of space and inform us as to the kinds of materials we might choose for designing spaces occupied by children under the age of five in order to maximize their spatial experience.

References

Bird, C. M., Capponi, C., King, J. A., Doeller, C. F., & Burgess, N. (2010). Establishing the boundaries: the hippocampal contribution to imagining scenes. *The Journal of Neuroscience, 30*(35), 11688-11695.

Bjerknes, T. L., Moser, E. I., & Moser, M. B. (2014). Representation of geometric borders in the developing rat. *Neuron*, *82*(1), 71-78.

Bullens, J., Nardini, M., Doeller, C. F., Braddick, O., Postma, A., & Burgess, N. (2010). The role of landmarks and boundaries in the development of spatial memory. *Developmental Science*, *13*(1), 170-180.

Burgess, N. (2008). Spatial cognition and the brain. *Annals of the New York Academy of Sciences*, *1124*(1), 77-97.

Burr, D., & Gori, M. (2012). Multisensory integration develops late in humans. In *The neural bases of multisensory processes* (2012)*,* Murray MM, Wallace MT editors, 345-362.

Cheng, K. (1986). A purely geometric module in the rat's spatial representation. *Cognition*, *23*(2), 149-178.

Cheng, K. (2008). Whither geometry? Troubles of the geometric module. *Trends in cognitive sciences*, *12*(9), 355-361.

Cheng, K., Huttenlocher, J., & Newcombe, N. S. (2013). 25 years of research on the use of geometry in spatial reorientation: a current theoretical perspective. *Psychonomic bulletin & review*, *20*(6), 1033-1054.

Cheng, K., & Newcombe, N. S. (2005). Is there a geometric module for spatial orientation? Squaring theory and evidence. *Psychonomic bulletin & review*, *12*(1), 1-23.

Cheng, K., & Newcombe, N. S. (2006). Geometry, features, and orientation in vertebrate animals: a pictorial review. *Animal spatial cognition: comparative, neural, and computational approaches. http://www. pigeon. psy. tufts. edu/asc/cheng*.

Derdikman, D., & Moser, E. I. (2010). A manifold of spatial maps in the brain. *Trends in cognitive sciences*, *14*(12), 561-569.

Dilks, D. D., Julian, J. B., Paunov, A. M., & Kanwisher, N. (2013). The occipital place area is causally and selectively involved in scene perception. *Journal of Neuroscience*, *33*(4), 1331-1336.

Doeller, C. F., & Burgess, N. (2008). Distinct error-correcting and incidental learning of location relative to landmarks and boundaries. *Proceedings of the National Academy of Sciences*, *105*(15), 5909-5914.

Doeller, C. F., King, J. A., & Burgess, N. (2008). Parallel striatal and hippocampal systems for landmarks and boundaries in spatial memory. *Proceedings of the National Academy of Sciences*, *105*(15), 5915-5920.

Epstein, R. (2005). The cortical basis of visual scene processing. *Visual Cognition*, *12*(6), 954- 978.

Epstein, R. (2008). Parahippocampal and retrosplenial contributions to human spatial navigation. *Trends in cognitive sciences*, *12*(10), 388-396.

Epstein, R. A., & Higgins, J. S. (2007). Differential Parahippocampal and Retrosplenial Involvement in Three Types of Visual Scene Recognition. *Cerebral cortex*, *17*(7), 1680- 1693.

Epstein, R., & Kanwisher, N. (1998). A cortical representation of the local visual environment. *Nature*, *392*(6676), 598-601.

Ferrara, K., & Landau, B. (2015). Geometric and featural systems, separable and combined: Evidence from reorientation in people with Williams syndrome. *Cognition*, *144*, 123-133.

Ferrara, K., & Park, S. (2016). Neural representation of scene boundaries. *Neuropsychologia, 89,* 180-190.

Gallistel, C. R. (1990). *The organization of learning* (pp. 317-350). Cambridge, MA: MIT press.

Garrad-Cole, F., Lew, A. R., Bremner, J. G., & Whitaker, C. J. (2001). Use of cue configuration geometry for spatial orientation in human infants (Homo sapiens). *Journal of Comparative Psychology*, *115*(3), 317.

Gee, A. P., Chekhlov, D., Calway, A., & Mayol-Cuevas, W. (2008). Discovering higher level structure in visual SLAM. *IEEE Transactions on Robotics*, *24*(5), 980-990.

Gogtay, N., Nugent, T. F., Herman, D. H., Ordonez, A., Greenstein, D., Hayashi, K. M., ... & Thompson, P. M. (2006). Dynamic mapping of normal human hippocampal development. *Hippocampus*, *16*(8), 664-672.

Golarai, G., Ghahremani, D. G., Whitfield-Gabrieli, S., Reiss, A., Eberhardt, J. L., Gabrieli, J. D., & Grill-Spector, K. (2007). Differential development of high-level visual cortex correlates with category-specific recognition memory. *Nature neuroscience*, *10*(4), 512-522.

Greene, M. R., & Oliva, A. (2009). Recognition of natural scenes from global properties: Seeing the forest without representing the trees. *Cognitive psychology*, *58*(2), 137-176.

Grill-Spector, K. (2003). The neural basis of object perception. *Current opinion in neurobiology*, *13*(2), 159-166.

Hartley, T., Burgess, N., Lever, C., Cacucci, F., & O'Keefe, J. (2000). Modeling Place Fields in Terms of the Cortical Inputs to the Hippocampus. *Hippocampus*, *10*, 369-379.

Hartley, T., & Lever, C. (2014). Know your limits: the role of boundaries in the development of spatial representation. *Neuron*, *82*(1), 1-3.

Hartley, T., Lever, C., Burgess, N., & O'Keefe, J. (2014). Space in the brain: how the hippocampal formation supports spatial cognition. *Phil. Trans. R. Soc. B*, *369*(1635), 20120510.

Hermer, L., & Spelke, E. S. (1994). A geometric process for spatial reorientation in young children. *Nature*, *370*(6484), 57-59.

Hermer, L., & Spelke, E. (1996). Modularity and development: The case of spatial reorientation. *Cognition*, *61*(3), 195-232.

Hermer-Vazquez, L., Moffet, A., & Munkholm, P. (2001). Language, space, and the development of cognitive flexibility in humans: The case of two spatial memory tasks. *Cognition*, *79*(3), 263-299.

Hermer-Vazquez, L., Spelke, E. S., & Katsnelson, A. S. (1999). Sources of flexibility in human cognition: Dual-task studies of space and language. *Cognitive psychology*, *39*(1), 3-36.

Hyde, D. C., Winkler-Rhoades, N., Lee, S. A., Izard, V., Shapiro, K. A., & Spelke, E. S. (2011). Spatial and numerical abilities without a complete natural language. *Neuropsychologia*, *49*(5), 924-936.

Huttenlocher, J., & Lourenco, S. F. (2007). Coding location in enclosed spaces: is geometry the principle?. *Developmental science*, *10*(6), 741-746.

Julian, J. B., Ryan, J., Hamilton, R. H., & Epstein, R. A. (2016). The occipital place are causally involved in representing environmental boundaries during navigation. *Current Biology*, *26*(8), 1104-1109.

Killian, N. J., Jutras, M. J., & Buffalo, E. A. (2012). A map of visual space in the primate entorhinal cortex. *Nature*, *491*(7426), 761-764.

Kosslyn, S. M., Pick Jr, H. L., & Fariello, G. R. (1974). Cognitive maps in children and men. *Child development*, 707-716.

Landau, B., & Lakusta, L. (2009). Spatial representation across species: Geometry, language, and maps. *Current opinion in neurobiology*, *19*(1), 12-19.

Learmonth, A. E., Newcombe, N. S., & Huttenlocher, J. (2001). Toddlers' use of metric information and landmarks to reorient. *Journal of experimental child psychology*, *80*(3), 225-244.

Lee, S. A. (2017). The boundary-based view of spatial cognition: a synthesis. *Current Opinion in Behavioral Sciences*, *16*, 58-65.

Lee, S. A., & Spelke, E. S. (2008). Children's use of geometry for reorientation. *Developmental science*, *11*(5), 743-749.

Lee, S. A., & Spelke, E. S. (2010a). A modular geometric mechanism for reorientation in children. *Cognitive psychology*, *61*(2), 152-176.

Lee, S. A., & Spelke, E. S. (2010b). Two systems of spatial representation underlying navigation. *Experimental Brain Research*, *206*(2), 179-188.

Lee, S. A., & Spelke, E. S. (2011). Young children reorient by computing layout geometry, not by matching images of the environment. *Psychonomic bulletin & review*, *18*(1), 192-198.

Lee, S. A., Sovrano, V. A., & Spelke, E. S. (2012a). Navigation as a source of geometric knowledge: Young children’s use of length, angle, distance, and direction in a reorientation task. *Cognition*, *123*(1), 144-161.

Lee, S. A., Winkler-Rhoades, N., & Spelke, E. S. (2012b). Spontaneous reorientation is guided by perceived surface distance, not by image matching or comparison. *PloS one*, *7*(12), e51373.

Lee, S. A., Vallortigara, G. Flore, M., Spelke, E. S., & Sovrano, V. A. (2013). Navigation by Environmental geometry: the use of zebrafish as a model. *Journal of Experimental Biology, 216(19), 3693-3699.*

Lever, C., Wills, T., Cacucci, F., Burgess, N., & O'Keefe, J. (2002). Long-term plasticity in hippocampal place-cell representation of environmental geometry. Nature, 416(6876), 90- 94.

Lever, C., Jeewajee, A., Burton, S., O'Keefe, J., & Burgess, N. (2009). Hippocampal theta Frequency, novelty, and behavior. *Hippocampus*, *19*(4), 409-410.

Lew, A. R. (2011). Looking beyond the boundaries: time to put landmarks back on the cognitive map? *Psychological bulletin*, *137*(3), 484.

Lew, A. R., Foster, K. A., Bremner, J. G., Slavin, S., & Green, M. (2005). Detection of geometric, but not topological, spatial transformations in 6-to 12-month-old infants in a visual exploration paradigm. *Developmental psychobiology*, *47*(1), 31-42.

Lew, A. R., Gibbons, B., Murphy, C., & Gavin Bremner, J. (2010). Use of geometry for spatial reorientation in children applies only to symmetric spaces. *Developmental science*, *13*(3), 490-498.

Lourenco, S. F., Addy, D., & Huttenlocher, J. (2009). Location representation in enclosed spaces: What types of information afford young children an advantage? *Journal of Experimental Child Psychology*, *104*(3), 313-325.

Maguire, E. (2001). The retrosplenial contribution to human navigation: a review of lesion and neuroimaging findings. *Scandinavian journal of psychology*, *42*(3), 225-238.

Mayer, U., Bhushan, R., Vallortigara, G., & Lee, S. A. (2017). Representation of environmental shape in the hippocampus of domestic chicks (Gallus gallus). *Brain Structure and Function*, 1-13.

Mou, W., & Zhou, R. (2013). Defining a boundary in goal localization: Infinite number o points or extended surfaces. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *39*(4), 1115-1027.

Nardini, M., Bedford, R., & Mareschal, D. (2010). Fusion of visual cues is not mandatory in children. *Proceedings of the National Academy of Sciences*, *107*(39), 17041-17046.

Newcombe, N., & Liben, L. S. (1982). Barrier effects in the cognitive maps of children and adults. *Journal of Experimental Child Psychology*, *34*(1), 46-58.

Newcombe, N. S., Ratliff, K. R., Shallcross, W. L., & Twyman, A. D. (2010). Young children's use of features to reorient is more than just associative: Further evidence against a modular view of spatial processing. *Developmental science*, *13*(1), 213-220..

O'Keefe, J., & Burgess, N. (1996). Geometric determinants of the place fields of hippocampal neurons. *Nature*, *381*(6581), 425-428.

O'Keefe, J., & Nadel, L. (1978). *The hippocampus as a cognitive map*. Oxford University Press, USA.

Park, S., Brady, T. F., Greene, M. R., & Oliva, A. (2011). Disentangling scene content from spatial boundary: complementary roles for the parahippocampal place area and lateral occipital complex in representing real-world scenes. *The Journal of Neuroscience*, *31*(4), 1333-1340.

Park, S., & Chun, M. M. (2009). Different roles of the parahippocampal place area (PPA) and retrosplenial cortex (RSC) in panoramic scene perception. *Neuroimage*, *47*(4), 1747-1756.

Park, S., Ferrara, K., & Landau, B. (2015). Impaired behavioral and neural sensitivity to boundary cues in Williams syndrome.*Journal of vision*, *15*(12), 115-115.

Quirk, G. J., Müller, R. U., & Kubie, J. L. (1990). The firing of hippocampal place cells in the dark depends on the rat's recent experience. *The Journal of Neuroscience*, *10*(6), 2008- 2017.

Ratliff, K. R., & Newcombe, N. S. (2008). Reorienting when cues conflict: Evidence for an adaptive-combination view. *Psychological science*, *19*(12), 1301-1307.

Save, E., Cressant, A., Thinus-Blanc, C., & Poucet, B. (1998). Spatial firing of hippocampal place cells in blind rats. *The Journal of Neuroscience*, *18*(5), 1818-1826.

Sheynikhovich, D., Chavarriaga, R., Strösslin, T., Arleo, A., & Gerstner, W. (2009). Is there a geometric module for spatial orientation? Insights from a rodent navigation model. *Psychological review*, *116*(3), 540-566.

Shusterman, A., & Spelke, E. (2005). Language and the development of spatial reasoning. *The innate mind: Structure and contents*, 89-106.

Silveira, G., Malis, E., & Rives, P. (2008). An efficient direct approach to visual SLAM. *IEEE transactions on robotics*, *24*(5), 969-979.

Solstad, T., Boccara, C. N., Kropff, E., Moser, M. B., & Moser, E. I. (2008). Representation of geometric borders in the entorhinal cortex. *Science*, *322*(5909), 1865-1868.

Spelke, E., Lee, S. A., & Izard, V. (2010). Beyond core knowledge: Natural geometry. *Cognitive Science*, *34*(5), 863-884.

Stewart, S., Jeewajee, A., Wills, T. J., Burgess, N., & Lever, C. (2014). Boundary coding in the rat subiculum. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, *369*(1635), 20120514.

Sutton, J. E., Twyman, A. D., Joanisse, M. F., & Newcombe, N. S. (2012). Geometry three ways: an fMRI investigation of geometric information processing during reorientation. *Journal of experimental psychology. Learning, memory, and cognition*, *38*(6), 1530-1541.

Tolman, E. C. (1948). Cognitive maps in rats and men. *Psychological review*, *55*(4), 189-208.

Torralba, A., Oliva, A., Castelhano, M. S., & Henderson, J. M. (2006). Contextual guidance of eye movements and attention in real-world scenes: the role of global features in object search. *Psychological review*, *113*(4), 766-786.

Twyman, A. D., & Newcombe, N. S. (2010). Five reasons to doubt the existence of a geometric module. *Cognitive science*, *34*(7), 1315-1356.

Twyman, A. D., Newcombe, N. S., & Gould, T. J. (2009). Of mice (Mus musculus) and toddlers (Homo sapiens): evidence for species-general spatial reorientation. *Journal of Comparative Psychology*, *123*(3), 342-345.

Wang, R. F., Hermer, L., & Spelke, E. S. (1999). Mechanisms of reorientation and object localization by children: a comparison with rats. *Behavioral neuroscience*, *113*(3), 475.

Yousif, S. R., & Lourenco, S. F. (2017). Are all geometric cues created equal? Children’s use of distance and length for reorientation. *Cognitive Development*, *43*, 159-169.

Chapter 2

Does a row of objects comprise a boundary?: How children miss the forest for the trees

Abstract

While navigation by boundary geometry has been widely documented, what defines a surface as a boundary has yet to be determined. Previous studies have shown that young children cannot use 2D arrays or an array produced by three or four freestanding objects arranged in a geometric fashion, even if very bright. Instead, children from 2 years of age are able to use even subtle geometric configurations as long as they are 3D and extended on the ground plane. Recent studies also showed that children can use 3D extended boundaries arranged in a rectangular formation even if they are segmented into 80 or 100 cm long walls. Why do children fail in using an array of objects and succeed in using an array of walls? How does the functionality of boundaries for navigation relate to their capacity of preventing vision and movement? How does the boundary continuity and length affect navigation? In our study, we started to answer these questions with children from 4 to 9 years old.

In Experiment 1, we tested them in a discontinuous rectangular array made up of 20 closely-aligned objects with an inter-object space of either 16 cm (Condition 1) or 8 cm (Condition 2). In Experiment 2 we tested children with the same objects arranged as four 50 cm-long continuous walls (Condition 1) or two 100 cm long continuous walls (Condition 2). Our results showed that children are not able to use the objects' array (Exp. 1) until they are 7, suggesting a late emergence of the capacity of extrapolating a geometric shape from a discontinuous structure, even if it was visually salient and prevented motion. Moreover, children succeeded in using both 50 cm compact walls and 100 cm walls (Exp. 2), confirming children from a very early age are able to use boundaries as long as they represent continuous and extended surfaces.

1.Introduction

Decades of past research pointed to separable mechanisms for processing objects and boundaries in navigation, in animals, as well as children (O'Keefe & Nadel 1978; Lee et al. 2010b, for review) and adults (Doeller, King & Burgess 2008). Experiments by Ken Cheng (1986) showed that rats, which were trained in a rectangular arena to go to one particular corner in order to get a food reward, tended to visit the correct corner and its geometric equivalent with the same frequency after disorientation, demonstrating they have encoded the geometric shape of the layout and are able to use it to reorient. Importantly, when provided with cues allowing them to disambiguate the two geometrically equivalent corners, like different visual patterns or different odors, rats ignored the featural information and tended to visit the same two corners with equal frequency. Interestingly, when rats were trained on over 30 trials to go to the correct corner when it was characterized by both distinctive geometric and featural information, after disorientation they tended to visit the correct corner with higher frequency. This showed they could learn by extensive training to associate the target location with the featural information, which was the first finding to suggest that navigation by geometry and landmarks might be mediated by different cognitive mechanisms. While landmark navigation was likely to obey the rules of cumulative, associative learning, the encoding of geometry might rest on a modular, spontaneous cognitive process which was quick and easy to activate. Consistent with this hypothesis, behavioral studies of spatial learning by human adults provided further evidence for distinct cognitive mechanisms for processing boundaries and landmarks (Doeller & Burgess 2008). In the study by Doeller and Burgess (2008), adults had to navigate in a virtual environment containing both an extended bordering surface and a freestanding object and they had to memorize the location of specific objects for a subsequent placement task. Subjects spontaneously encoded target positions relative to the border, and their encoding was resistant to interference from other memory associative processes, suggesting boundary learning to be automatic and incidental. On the other hand, landmark encoding was sensitive to interference, thus the authors concluded that landmark related navigation obeys to distinct learning rules with respect to boundary-related navigation. They hypothesized landmarks to be responsive to a form of cumulative, associative learning. Such an explanation is likely to be at the basis of the primacy in the spontaneous encoding of boundaries, which was shown to be present across different tasks and different species and in toddlers as well (see General Discussion, Cheng & Newcombe 2005; 2006 for review). Neuro-imaging studies in adults suggested that such a disparity in the use of geometry and landmarks during navigation is rooted in a dissociation in the processing of spatial information in the brain. In a virtual reality task, where subjects had to learn a location either by the use of landmarks or boundaries, activation of the right hippocampus was shown for processing locations with respect to environmental boundaries, and activation of the right dorsal striatum was shown for processing landmark-related locations (Doeller, King, & Burgess 2008). Further neuro-imaging studies (Bird et al. 2010) showed hippocampal activity to be increasingly modulated by the greater frequency of horizontal enclosing walls, rather than by vertical elements.

Electrophysiological studies in rodents complemented human neuro-imaging and behavioral studies by showing that while place cells are sensitive to distances and directions from the boundaries of the testing environment (O'Keefe & Burgess 1996) and to the geometric shape of the layout, they are less sensitive to changings in texture or color (Lever et al. 2002). Moreover, some studies showed that these cells are insensitive to objects positioned at the center of the apparatus, but are sensitive to geometric configurations of objects when they are attached to the walls (Cressant, Muller & Poucet 1997).

As we saw in the General Introduction, behavioral studies (Hermer & Spelke 1994; 1996) showed that after being disoriented, children, as well as rats, used the geometric shape of the layout to reorient when an object was hidden at one corner of a rectangular chamber. Importantly, children, as well as rats again, failed the task when the two corners were disambiguated by means of a colored panel attached on one wall and still tended to exclusively rely on the geometric shape of the layout. This showed that also in children, geometric and featural information are processed differently. Only around the age of 5-7 children were shown to acquire the capacity to solve the reorientation task in the rectangular chamber with the red panel by integrating featural and geometric information (Hermer-Vazquez et al. 2001).

Behavioral studies with children have shown that they also failed in using geometric arrays made up of discrete objects for reorienting. Not only did they failed in using rectangular arrays of tall columns (Lee & Spelke 2008), but also in using arrays of objects arranged in an asymmetrical configuration, such that their heading and direction were specified unambiguously. Gouteux and Spelke (2001) tested children with an arrangement of three indistinguishable boxes arranged in a triangular fashion (both in a right and in an isosceles triangle) and showed children didn't succeed in reorientation tasks, only succeeded if not disoriented. Interestingly, children succeeded when the objects were distinguishable one from the other, such that they could correctly find the right box that served as the location of the sticker. Moreover Lee, Shusterman and Spelke (2006) tested children with three containers arranged in a triangular fashion. Among these three containers, two of them were indistinguishable to each other and one of them was different from the other two by both shape and color. On disoriented trials, children were able to correctly locate the position of the sticker when it was hidden under the distinctive container, but not when it was hidden under one of the equal ones. This experiment confirmed children could use the distinctive container as a direct cue for reorientation, but not as an indirect cue for finding the correct location of the sticker. Additionally, Lee and Spelke (2011) showed that children not only failed at the reorientation task with a rectangular array of four tall columns (Lee & Spelke 2008), but they also failed when the columns were made very bright and were connected by a cable that underlined the geometric configuration and significantly prevented movement.

This failure in using the geometric configurations of objects indicates that sensitivity for geometry is found only for 3D *extended surfaces.* Of note, children were shown to succeed also when the surfaces were segmented. Indeed Lee et al. (2012) tested children with a rectangular configuration of 100 cm segmented walls and found out that children succeeded in this task as long as the walls were arranged in a rectangular fashion, but not in a squared fashion, indicating children can use the geometric properties of rectangular arrays of even segmented surfaces as long as they are continuous and extended. Additionally, in Chapter 1 (Gianni, De Zorzi & Lee 2018), we showed that children succeeded even when the segmented surfaces were 80 cm long (even if inserted into a transparent array).

Why is the array of walls processed differently than an array of objects? Which is the limit in size and length at which a boundary start/stop to be perceived as different from an object and as a valid cue for navigation? It might be argued that in the experiments we reviewed above, the object configuration children failed with (either triangular as in Gouteux and Spelke 2001, or rectangular, as in Lee and Spelke 2008; 2011) wasn't sufficiently dense (only four objects) to underline the geometric configuration (Newcombe & Liben 1972) and to make it clearly detectable for children. It is also possible to argue that children failed because these configurations were not sufficiently dense to prevent movement, assuming sensitivity to boundaries to be specifically related to their capacity of being relevant obstacles to movement (Benhamou & Poucet 1998). In fact, it is still not clear how the use of boundaries in navigation relates to their capacity of preventing movement (Kosslyn, Pick & Fariello, 1974), or how their length and solidity/continuity factor plays a role into their conceptualization as boundaries (Lee, Sovrano & Spelke, 2012), and finally, if their conceptualization is submitted to fundamental changes over the course of development. Conversely, it is possible to argue that young children failed in the reorientation task with an arena made up objects because of the particular nature of the stimuli they were presented with; as we saw in the studies we reviewed above, boundaries and objects constitute qualitatively different stimuli in navigation, as they are processed by distinct cognitive mechanisms, obey to different rules and are encoded by different parts of the brain. Since children were shown to have difficulty in encoding objects or features in the navigable environment up to a certain age, it is possible to presume this difficulty might affect children's capacity for processing boundaries made up of discrete objects.

In our study, we wanted to test these hypotheses and investigate whether young children were sensitive to boundaries made up of a dense configuration of closely-aligned objects in a reorientation task, or whether, since objects and boundaries are processed differently, they presented no sensitivity for arrays made up of objects, as in previous studies. We were also interested in investigating if, how and when the ability to process those arrays occurs in development (Experiment 1), as previous studies indicated the capacity of processing objects in navigation and of integrating geometric and featural information might occur later in development with respect to the capacity of processing continuous boundaries (Lee et al. 2006; Lehnung et al. 1998) and this late emergency might drive developmental changes in children's representation of boundaries made up of aligned objects.

Additionally, we asked ourselves whether children's use of continuous and discontinuous boundaries' structures was distinct and whether it followed different developmental patterns. Accordingly, we also tested children with continuous arrays (Experiment 2).

In order to maximize the chance to observe developmental changes in the use of boundaries made up of objects, we chose to focus on a wide age range and to study the use of discontinuous boundaries (Experiment 1) and continuous boundaries (Experiment 2) in different age groups. Moreover, since boundaries and objects activate different cognitive mechanisms in navigation, we were interested in understanding which properties distinguish a boundary from an object, therefore we decide to start investigating at which length a boundary start/stop to be perceived as an object. Therefore, in Experiment 2, we tested children with continuous walls of different lengths. We predicted young children would be able to succeed in the reorientation task if the boundary's length was sufficient in order for it to be perceived as a proper boundary and we predicted children's failure if the boundary's length was not sufficient for it to be perceived as a proper boundary and it was perceived, rather, as a single object.

In the present study, we tested 147 children from 4 to 9 years of age in four different rectangular arrays consisting of 20 free-standing objects (see Figure 8 and 11). In Experiment 1 (discontinuous boundaries), the objects were arranged in a rectangular fashion with an inter-object spacing of either 16 cm (Condition 1) or 8 cm (Condition 2). Experiment 1 was designed in order to investigate whether children still failed with a configuration of objects that was sufficiently dense to underline the geometric figure and to prevent children's movement. In Experiment 2 (continuous boundaries), objects were aligned to form four compact walls of 50 cm (Condition 1), or they were made into two longer compact walls (100 cm long, Condition 2). This experiment was designed in order to investigate children's reorientation behavior with walls of different lengths.

2. Methods

Experiment 1

2.1 Participants

Participants were 96 healthy children ranging from 37 to 119 months of age who were recruited from daycares and recreational centers in and around Rovereto, Italy. They were sampled independently of their demographic or socio-economic characteristics. Subjects were randomly split between Conditions 1 and 2 with a balanced number of males and females: 48 children, 25 boys and

23 girls were tested in Condition 1 (16 cm inter-object distance), and an equal number of children, 27 boys and 21 girls, were tested in Condition 2. Participants were divided into two age groups: 4-6 years old and 7-9 years old. In Condition 1 (16 cm inter-object distance), we had 24 subjects in the younger group (37 to 83 months, *Mean*=65, *SD*=11.67: nine 4-year-olds, seven 5-year-olds, eight 6-year-olds) and 24 subjects in the older group (73 to 119 months, *Mean*=102.18, *SD*=9.63: eight 7-year-olds, nine 8-year-olds, seven 8-year-olds). Similarly, in Condition 2 (8 cm inter-object distance), we had 24 subjects in the younger group (37 to 83 months *Mean*=66.67, *SD*=10.31: eight 4-year-olds, eight 5-year-olds, eight 6-year-olds) and 24 subjects in the older group (73 to 119 months, *Mean*=102.22, *SD*=10.8: six 7-year-olds, ten 8-year-olds, eight 9-year-olds). The participants visited the laboratory accompanied by an adult, usually a parent. At the end of the test each child was given a certificate of participation and a souvenir (usually a small toy). 14 additional participants (nine in Condition 1 and five in Condition 2) were omitted from the data analysis because either refused to participate or failed to complete the entire test (four trials) or we could not ensure they were correctly disoriented because they had four choices of the target corner and guessed the correct location of the door at the "disorientation check" (see the Experimental Procedure). Informed consent from the parent or guardian and verbal consent from the child were obtained prior to the study.

2.2 Experimental Setting

Experiments took place in a soundproof room of the laboratory. A circular fabric black tent was hung from the ceiling forming a circular enclosure (2.1 m diameter, Figure 7). One side of the enclosure had an opening that was used as the entrance. In order not to provide any spatial cue besides the experimental apparatus, the opening was made in such a way that it was impossible for the subject to notice it once it was closed.. The floor was a uniform light-grey color. At the center of the enclosure was the experimental arena (170 cm by 110 cm rectangular shape (external perimeter) made up of 20 closely-aligned objects of 30 cm height and 10 cm width.) White inverted cups were positioned at each corner of the experimental arena (see Figure 7). Hanging from the center of the ceiling of the testing room, was a video-camera recording the experiment and projecting it to a screen located in an adjacent room. In this room, a second experimenter watched the experiment and registered children's responses.

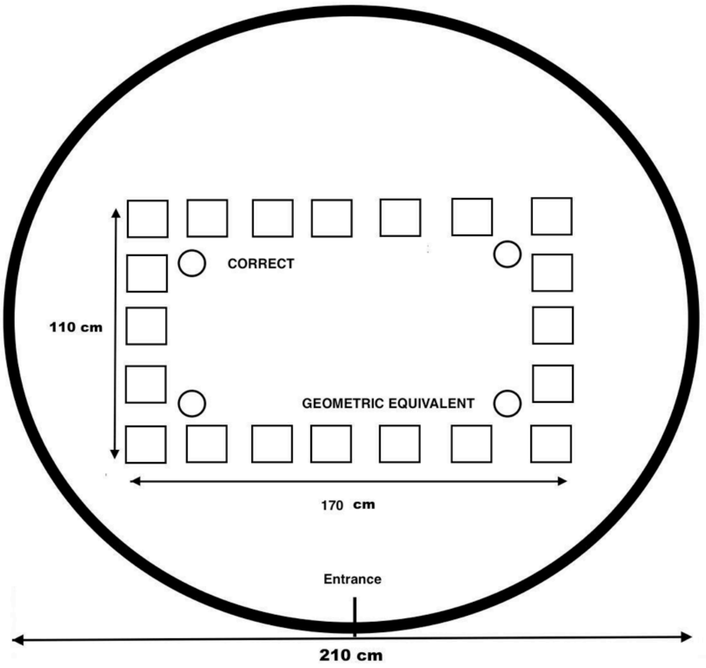


Figure 7. Experimental setting, schematic view from above. Objects arranged as in Condition 1, Experiment 1.

2.3 Design

The experiment consisted of four separate trials where the goal position was kept in the same location in order to avoid confusion across different trials. We chose this experimental methodology, as opposed to a methodology in which the target position varies across trials (Hermer-Vazquez, Spelke & Katsnelson 1999), on the basis of previous reorientation studies (Hermer & Spelke 1994; Lee & Spelke 2008, 2010a, 2011) and in order to avoid memory interference from previous trials. Previous studies using the same method (as well as our study - see Results section) didn't report any effect of training across trials affecting the results. Equal numbers of children were tested with each corner as the target. The direction in which children faced at the end of the disorientation procedure (one of the four walls of the rectangular arena) was varied across trials and counterbalanced across participants.

In order to investigate the use of environmental geometry (namely by the geometric information provided by the testing apparatus), the total proportion of correct and geometrically correct first choices was computed for each subject (C+G proportion). Scores were averaged across subjects for every age group. A univariate ANOVA was used to compare between-subjects variables (age group, sex and condition). Independent-sample t-tests were used to compare across age groups.

2.4 Experimental Procedure

Once in the laboratory, children were accompanied into the play-area where they could get familiar with the environment and the experimenter. Afterwards, the children entered the experimental room and the circular tent accompanied by the experimenter. After placing the children at the center of the experimental apparatus, the experimenter hid a sticker under a cup in one predetermined corner taking care children were watching. Then he put a blindfold on the children and rotated them on the same spot for ten seconds. The experimenter then stopped at a predetermined facing direction, while staying behind the children. The children then had the blindfold removed and were encouraged to search for the sticker. First choices were registered. If the children didn't find the sticker at their first choice, the experimenter showed them the correct location. The procedure was repeated for four consecutive trials. Children were rewarded with a sticker at every correct choice. After the four trials, children were submitted to a battery of questions (post-tests, see Section 5) aimed at investigating their mental representation of the apparatus. After the post-tests, while standing at the center of the room, subjects were submitted to a "disorientation check"; they were asked to point to the position of door. This was done in order to check whether subjects had been correctly disoriented such that they could not remember the correct position of the entrance. Subjects who both got four trials correct (indicating the target corner for four times) and correctly located the door, were omitted from the dataset because we could not ensure they were completely disoriented. The parents watched the children from a screen connected to the video camera alongside the second experimenter in the adjacent room. All experiments were approved by the Ethical Committee of the University of Trento and conducted in accordance with the institutional guidelines for human subject testing.

3. Experiment 1

The goal of this first experiment was to test whether the spacing between objects influences the development of children's representation of the array as a coherent or continuous structure. To this aim, we tested children with a rectangular discontinuous object-configuration in two different conditions. In Condition 1, we investigated children's spatial reorientation within a rectangular arena made up of 20 closely aligned rectangular prisms (30 cm height, 10 cm width) with a homogeneous inter-objects space of 16 cm (Figure 8 a). In Condition 2, we tested children's spatial reorientation in a rectangular arena made up of the same 20 objects, but with an inter-object space of 8 cm, grouped into four distinct segments (Figure 8 b). We chose to group the object into four distinct segments, instead of just increasing the number of objects from Condition 1, in order to keep the same amount of visual white matter for Condition 1 and 2.

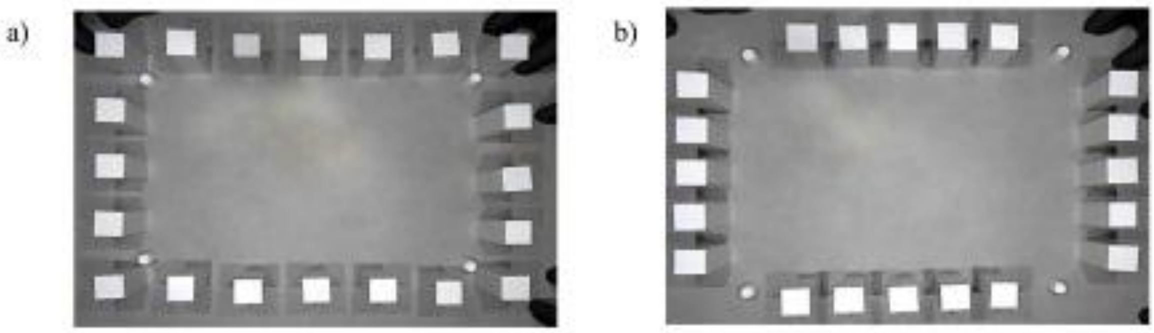


Figure 8. a) Apparatus used in Experiment 1, Condition 1: 20 objects (30 cm height, 10 cm width) were aligned with an inter-objects space of 16 cm to form a rectangular arena with discontinuous surfaces of 170 X 110 cm. b) Apparatus used in Experiment 1, Condition 2: 20 objects (30 cm height, 10 cm width) were aligned to form 4 segments of a rectangular arena (170 X 110 cm).

4. Post-tests

After the experiment, while standing in the experimental room at the center of the apparatus, subjects were asked a set of questions aimed at investigating their mental representation of the experimental apparatus. In particular, we investigated if they correctly detected the rectangular shape of the apparatus (even if the configuration was discontinuous) either in the 3D environment or on a schematic drawing (question 1 and 3) and if they perceived the discontinuous boundaries as proper walls (question 2). The rationale for these questions was to explore how the physical appearance of the apparatus, made up of discrete objects, affected children's representation of the boundaries. Specifically, we wanted to investigate whether the material configuration and aspect of the apparatus made up of discrete entities interfered with the representation of boundaries such that they could not be perceived as continuous walls and the geometric properties of the layout, e.g. its rectangular configuration, were made difficult to detect, particularly for Experiment 1, Condition 1 and 2 (discontinuous boundaries).

First, subjects were asked by the experimenter, "In this room there is a shape, can you tell me which one?" Secondly, they were asked, "How many walls do you see?" Thirdly, they were shown a paper sheet with two schematic drawings of the experimental room; one with a circle surrounding a square and one with circle surrounding a rectangle (the correct one, see Figure 9). Subjects were asked by the experimenter to point at the drawing they thought correctly represented the shape of the experimental room. The same drawings were shown two times (and the same question was repeated), either horizontally or vertically oriented.

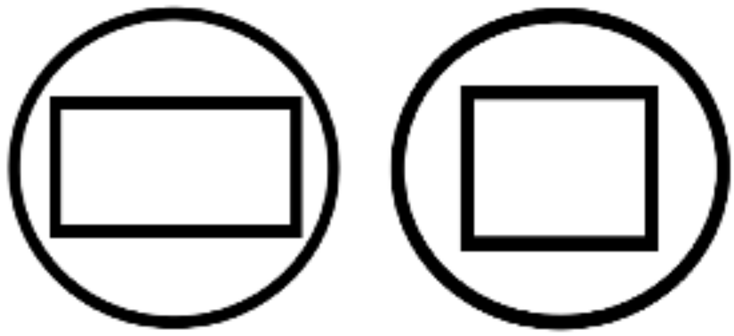


Figure 9. Schematic drawings of the experimental room (drawn on a sheet of paper) that were shown to the participants for question 3 of the post-tests. Participants were asked to point at the picture that they thought corresponded to the experimental room.

5. Results

A univariate ANOVA with between-subjects variables age group, sex and condition was used to investigate differences in children's performance. The results showed a significant effect of age group ($F(7,88)=13.94$, $p<0.001$) a non-significant effect of condition ($F(7,88)=0.01$, $p=0.91$) and a non-significant effect of sex ($F(7,88)=0.43$; $p=0.83$). Since there was no significant effect of condition and sex, results of condition 1 and condition 2 were collapsed and the sex variable was not further considered. One-sample t-tests were used to compare children's performances in the two age groups against the level of chance (0.5). They showed the performance of children in the younger age group (4 to 6 years) was not different than the level of chance ($t(47)=1.09$; $p=0.56$, Bonferroni corrected), while the performance of the older age group (7 to 9 years) was significantly above the level of chance ($t(47)=6.93$; $p<0.001$, Bonferroni corrected). Given the discrete nature of the variables under analysis (i.e. in four trials, the geometrically correct searches were not continuous), we confirmed these findings by comparing performance across age groups using non-parametric statistics (Mann-Whitney $U = 656$, $p = 0.0001$).

In order to ensure that children were fully disoriented and didn't choose the correct corner significantly more than its geometric equivalent by being guided by any other cue rather than environmental geometry, we compared the proportion of correct and geometrically equivalent searches for each age group. The results showed that children could not distinguish the correct corner from its geometric twin, both in the 4-6-year-old group ($t(47) = 0.10$; $p = 0.23$) and in the 7-9-year-old group ($t(47) = 0.78$; $p = 0.11$).

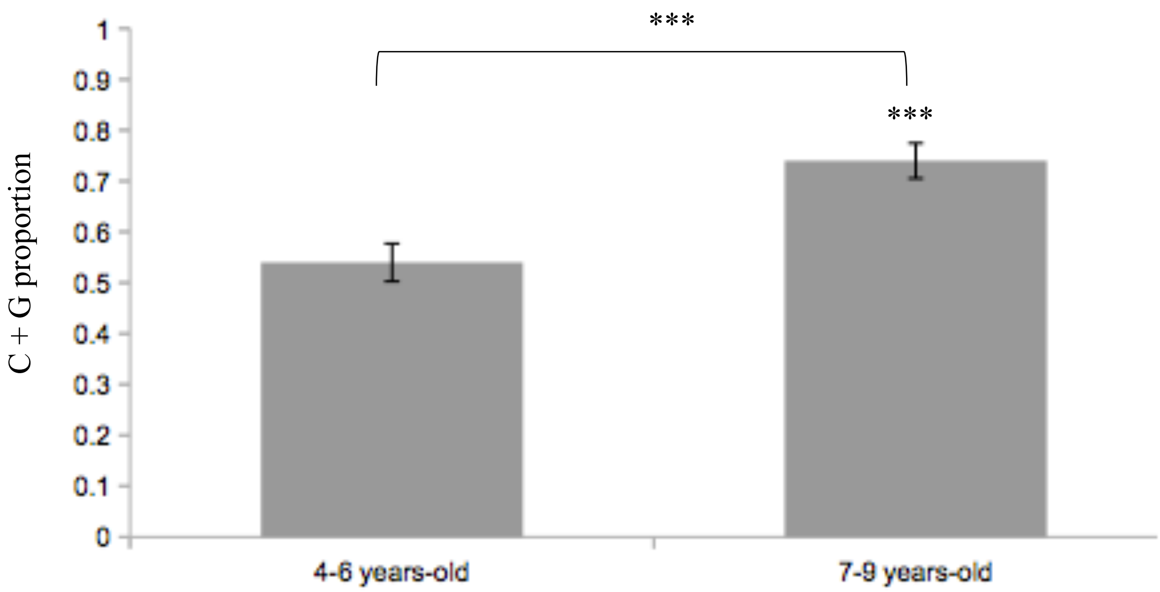


Figure 10. Proportions of C+G (correct + geometric equivalent) choices averaged across age groups for Condition 1 and 2 (Experiment 1) collapsed.

Experiment 2

6. Methods

6.1 Participants

Participants were 51 healthy children ranging from 37 to 119 months of age who were recruited from daycares and recreational centers in and around Rovereto, Italy. Subjects were divided into two groups; one group was tested in only one Condition (either 1 or 2) and the second group was tested in both Conditions 1 and 2. In the first group (27 subjects) subjects were randomly split between Conditions 1 and 2 (and tested only in one condition) with a balanced number of males and females: 14 children, (10 boys and 4 girls) were tested in Condition 1, while 13 children (6 boys and 7 girls), were tested in Condition 2. Participants were divided into two age groups: 4-6 year-olds and 7-9 year-olds. In Condition 1 (only) (four walls of 50 cm length), we had eight subjects in the younger group (37 to 83 months, *Mean*=64, *SD*=11.51: 2 4-year-olds, three 5-year-olds, three 6-year-olds) and six subjects in the older group (73 to 119 months, *Mean*=101.22, *SD*=7.77: two 7-year-olds, two 8-year-olds, two 9-year-olds). Similarly, in Condition 2 (only) (8 cm inter-object distance), we had seven subjects in the younger group (37 to 83 months *Mean*=67, *SD*=11.23: three 4-year-olds, two 5-year-olds, two 6-year-olds) and six subjects in the older group (73 to 119 months, *Mean*=102.22, *SD*=10.8:

two 7-year-olds, two 8-year-olds, two 9-year-olds).

In the second group (24 subjects, 11 boys and 13 girls), subjects were tested in both conditions 1 and 2. The order of conditions in which they were tested was varied and counter-balanced across subjects. Participants were divided into two age groups: 4-6 year-olds and 7-9 year-olds. There were 12 subjects in the younger group (4 to 6 years of age, 37 to 83 months: four 7-year-olds, four 8-year-olds, four 9-year-olds) and 12 in the older group (7 to 9 years of age, 73 to 119 months: four 7-year-olds, four 8-year-olds, four 9-year-olds).

The participants visited the laboratory accompanied by an adult, usually a parent. At the end of the test each child was given a certificate of participation and a souvenir (usually a small toy). Ten additional participants (five in Condition 1 and 5 in Condition 2) were omitted from the data anlysis because they either refused to participate entirely or failed to complete the entire test (four trials) or we could not ensure they were correctly disoriented since they had four choices of the target corner and guessed the correct location of the door at the "disorientation check" (see the Experimental Procedure). Informed consent from the parent or guardian and verbal consent from the child were obtained prior to the study.

6.2 Experimental Setting, Design and Experimental Procedures

The experimental setting (except for the apparatus we describe below), the design and the experimental procedures were the same as in Experiment 1. The procedures for the post-tests were also the same, except for the fact that among subjects who were tested both in Condition 1 and 2, half received post-test questions relative to the four walls Condition (Condition 1) and half of them received questions relative to the two walls Condition (Condition 2).

The goal of experiment 2 was to test how continuous surfaces of different length affect children's spatial representation. To this aim, we tested children with continuous surfaces in two different conditions. In Condition 1, we tested children with an arena (a 170 cm by 110 cm external rectangular perimeter) made up of four compact 50 cm long continuous walls (obtained by closely aligning the same 20 objects we used in Experiment 1, Figure 11 a). In Condition 2, we tested children with an arena made up by the same objects forming two 100 cm long compact walls facing two opposite sides (Figure 11 b). At each corner of the arena was placed a white inverted cup that served as a hiding place for the stickers.

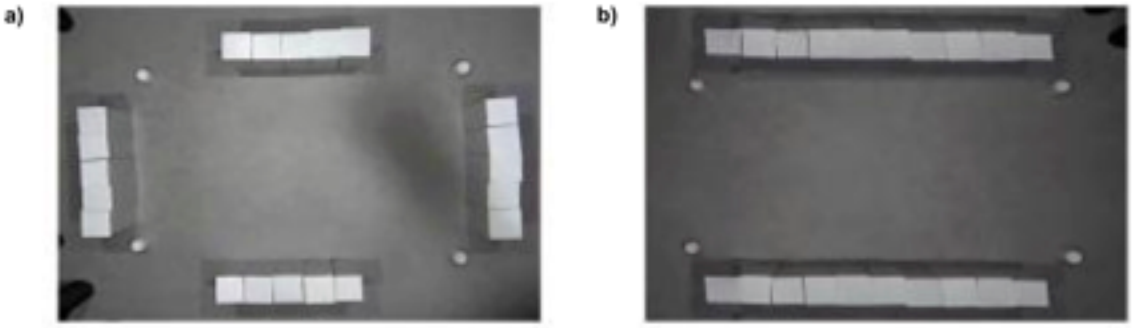


Figure 11. a) Apparatus used in Experiment 2, Condition 1: 20 objects were aligned to form four continuous walls of 50 cm length forming a rectangular shape (170 X 110 cm). b) Apparatus used in Experiment 2, Condition 2: 20 objects were aligned to form two continuous 100 cm long walls marking two long borders of a rectangular shape of 110 X 170 cm.

7. Results

Children who participated in both Condition 1 and Condition 2 did not perform differently from those who were only tested in one condition (condition 1: Mean=0.67, SEM=0.04, condition 2: Mean=0.80, SEM=0.05). Therefore, their performances in the two conditions were analyzed separately.

A univariate ANOVA with between-subjects variables age group, sex and condition was used to investigate differences in children's performance. The results showed a non-significant effect of age group ($F(7,68)=1.82$, $p=0.18$) a non-significant effect of condition ($F(7,68)=2.31$, $p=0.13$) and a non-significant effect of sex ($F(7,68)=0.79$; $p=0.37$). Since there was no significant effect of condition and sex, results of condition 1 and condition 2 were collapsed and the sex variable was not further considered. Additionally, one-sample t-tests were used to compare children's performances in the two age groups against the level of chance. The t-tests showed that in the younger age group, children performed significantly above the level of chance ($t(47)=6.93$; $p<0.001$, Bonferroni corrected). In fact, children performed significantly above the level both in condition 1 ($t(19)=2.60$; $p=0.02$, Bonferroni corrected), and in Condition 2, ($t(18)=4.02$; $p=0.002$, Bonferroni corrected). The older age group also performed significantly above the level of chance ($t(36)=7.11$; $p<0.001$, Bonferroni corrected), (both in Condition 1, $t(17)=4.27$; $p=0.002$, Bonferroni corrected, and in Condition 2, $t(18)=5.75$; $p<0.001$, Bonferroni corrected). Given the discrete nature of the variables under analysis (i.e. in four trials, the geometrically correct searches are not continuous), we confirmed these findings by comparing performance across age groups using non-parametric statistics (Mann-Whitney $U = 582$, $p = 0.13$).

In order to ensure that children who were tested in both conditions and children who were tested in only one condition did not perform differently, we compared the performances of these two groups for any age group using independent-sample t-tests. The results showed that there was no significant difference between these two groups both in Condition 1 for the two age groups (4-6 years old=t(18)=0.66; p=0.45; 7-9 years old=t(16)=0.34; p=073) and in Condition 2 for the two age groups (4-6 years old=t(17)=0.74; p=0.46; 7-9 years old=t(16)=0.36; p=0.72).

In order to ensure that children were fully disoriented and didn't choose the correct corner significantly more than its geometric equivalent by being guided by any other cue rather than environmental geometry, we compared the proportion of correct and geometrically equivalent searches for each age group. The results showed that children could not distinguish the correct corner from its geometric twin both in the 4-6-year-old group ($t(38) = 0.31$; $p = 0.75$) and in the 7-9-year-old group ($t(34) = 0.55$; $p = 0.58$).

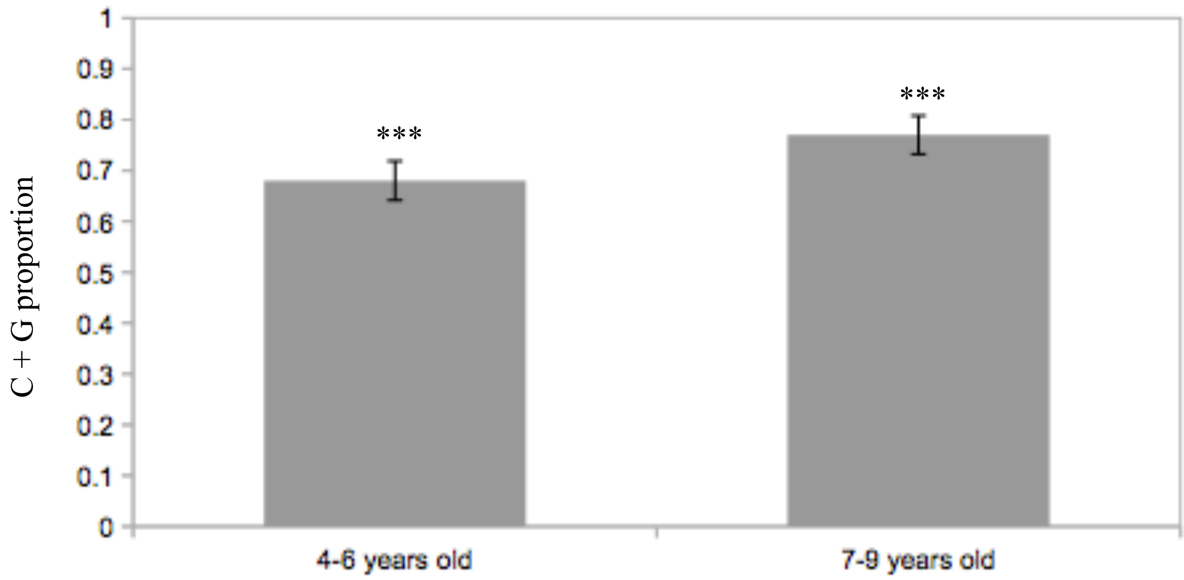


Figure 12. Proportions of C+G (correct + geometric equivalent) choices averaged across age groups for Condition 1 and 2 (Experiment 2) collapsed. *=p<0.05; **=p<0.01; ***=p<0.001.

8. Overall Results-Experiment 1 and 2

We compared the results of Experiments 1 (discontinuous boundaries) and 2 (continuous boundaries) to assess whether there were differences between conditions that provided discrete objects (Experiment 1, both Conditions) and those that provided continuous boundaries (Experiment 2, both Conditions, the performances of children who participated both in Condition 1 and in Condition 2 were analyzed separately as for the Experiment 2 results' section). In order to analyze differences between these two Experiments a univariate ANOVA with between-subjects variables sex, age group and "continuity" (indicating either discontinuous or continuous boundaries) was computed. It showed a non-significant effect of sex (F(7, 164)=0.16; p=0.68), a significant effect of age group ($F(7, 164)=13.49$; $p<0.001$) and a significant effect of continuity ($F(7,164)=4.21$; $p=0.04$) however there was not a significant interaction between the variables continuity and age groups ($F(7, 164)=2.56$, $p=0.11$). These results were further investigated using post-hoc pairwise t-tests. The t-tests showed there was an overall significant difference between the 4-6year-old group and the 7-9-year-old group ($t(170)=3.88$; $p<0.001$). Given the discrete nature of the variables under analysis (i.e. in four trials, the geometrically correct searches are not continuous), we confirmed this finding by comparing performance across age groups using non-parametric statistics (Mann-Whitney $U = 2503$, $p = 0.0001$). The t-tests also showed the overall difference between discontinuous (Experiment 1) and continuous boundaries (Experiment 2) was significant ($t(170)=2.09$; $p=0.037$), this finding was also partially confirmed using non-parametric statistics (Mann-Whitney $U = 3054$, $p = 0.057$). This difference was further explored separately for the two age groups. Results showed that the difference between the two continuity conditions (discontinuous and continuous boundaries, Experiment 1 and 2, respectively) was significant for the younger age group (4-6 years old) ($t(85)=2.59$; $p=0.02$, Bonferroni corrected, non-parametric statistics: Mann-Whitney $U = 656$, $p = 0.013$) and non-significant for the older age group ($t(83)=0.48$; $p=1$, Bonferroni corrected, non-parametric statistics: Mann-Whitney $U = 844$, $p = 0.68$).

Figure 14c, which plots performance by age in months, suggests a developmental change in the First Experiment (discontinuous boundaries) that is not present in the Second Experiment (continuous boundaries). Two tailed t-tests against the level of chance for the First Experiment (Experiment 1, Figure 14a) and the Second Experiment (Experiment 2, Figure 14b) are shown for each age, respectively for 4-year-olds, 5-year-olds, 6-year-olds, 7-year-olds, 8-year-olds and 9-year-olds.

In order to further explore the age effects, the data were broken down into six different age groups (4-year-olds, 5-year-olds, 6-year-olds, 7-year-olds, 8-year-olds and 9-year-olds) for both experiments. Univariate ANOVAS with year-group as independent variable and the proportion of geometrically correct searches (correct + geometrically equivalent corners) as the dependent variable were used to explore differences in performance by age in years for the two experiments. They showed a significant effect of year group for the First Experiment (discontinuous boundaries) (F=5, 90)=3.24, p=0.01), while the same effect was not significant for the Second Experiment (continuous boundaries) (F=5,70)=1.58, p=0.17). We confirmed this finding by using non-parametric statistics: First Experiment, test di Kruskal-Wallis, Chi-square=15.509; $p=0.008$; Second Experiment, Chi-square=5.723; $p=0.33$.

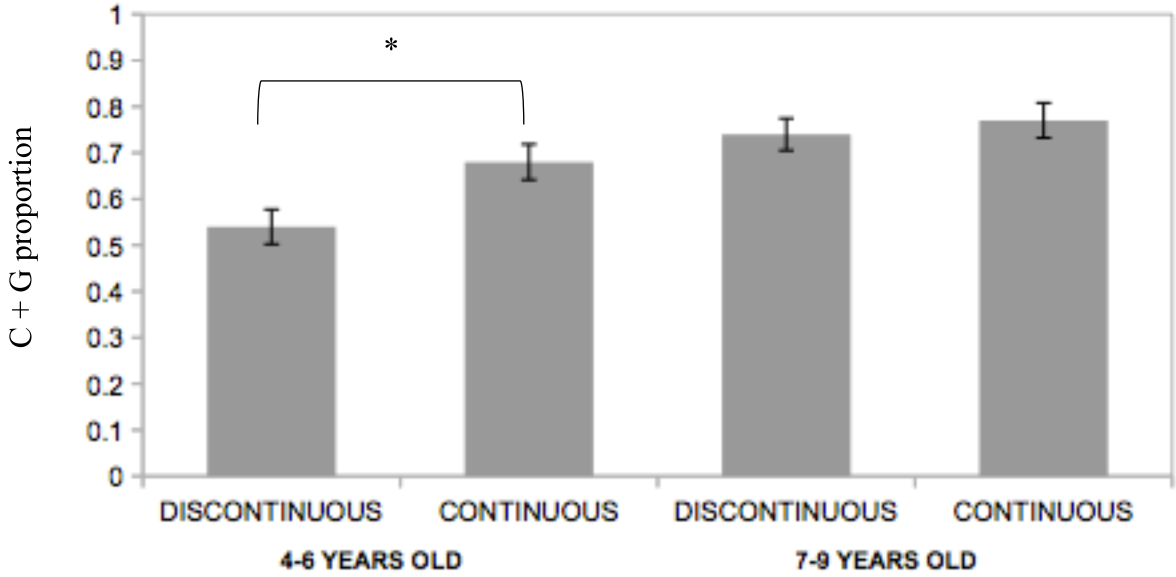


Figure 13. Proportions of C+G (correct + geometric equivalent) choices averaged across discontinuous boundary condition (Experiment 1) and continuous boundary condition (Experiment 2) and across age groups. *=p<0.05; **=p<0.01; ***=p<0.001.

Experiment 1, Discontinuous Boundaries

a)

YEARS	NUMBER OF SUBJECTS	T-TEST AGAINST 0.5	P-VALUE
4	16	$t(16)=0.23$	$p=0.81$
5	14	$t(14)=0.76$	$p=0.45$
6	15	$t(15)=0.84$	$p=0.41$
7	13	$t(13)=4.37$	$p=0.001$**
8	18	$t(13)=3.17$	$p=0.005$**
9	14	$t(11)=4.79$	$p<0.001$***

Experiment 2, Continuous Boundaries

b)

YEARS	NUMBER OF SUBJECTS	T-TEST AGAINST 0.5	P-VALUE
4	11	$t(11)=1.10$	$p=0.021$*
5	13	$t(13)=1.09$	$p=0.005$**
6	12	$t(12)=1.17$	$p=0.071$
7	11	$t(13)=2.74$	$p=0.009$**
8	11	$t(13)=4.83$	p<0.001***
9	12	$t(11)=6.51$	$p<0.011$*

c)

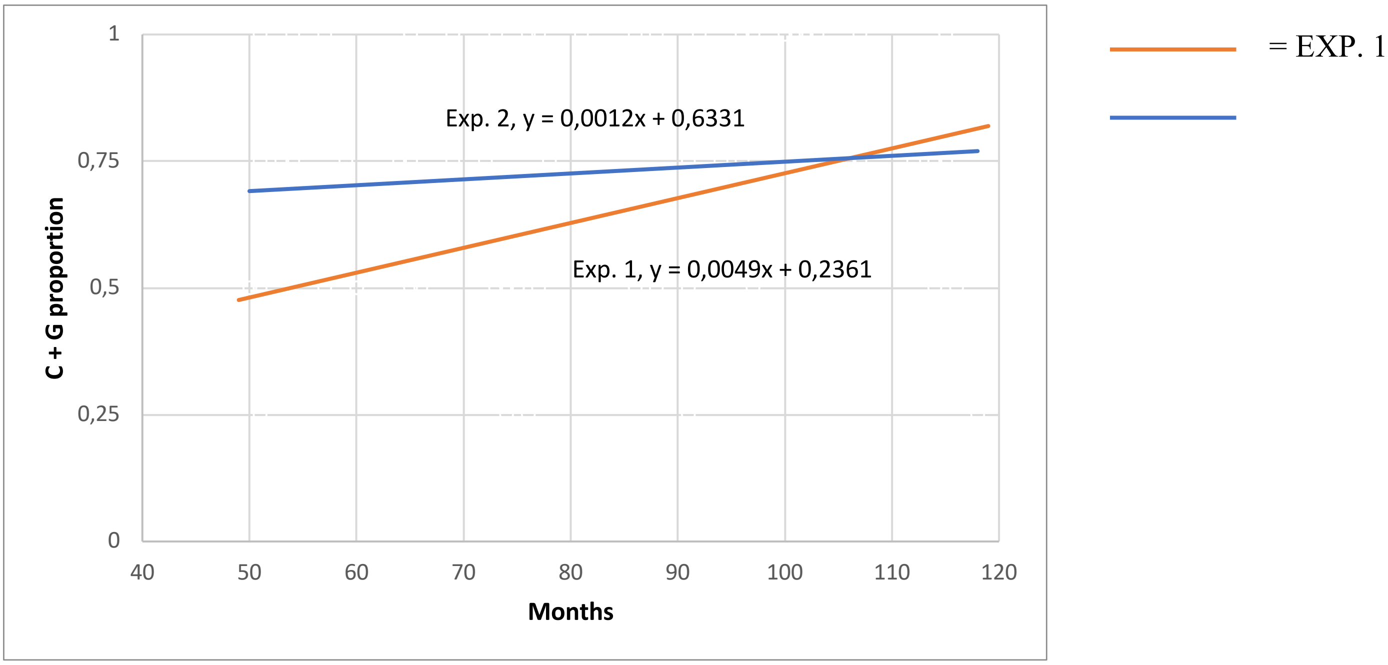


Figure 14. *a)* The table presents the number of subjects, the values of the t-tests against the level of chance and their p-value for Experiment 1 (discontinuous boundaries). *b)* The table presents the number of subjects, the values of the uncorrected t-tests against the level of chance and their p-value for Experiment 2 (continuous boundaries). *c)* Lines of tendency with the relative equations derived from the scatterplot of age in months by proportion of C+G responses for Experiment 1 (red) and Experiment 2 (blue).

9. Post-test results

For analyzing the post-test data, we established a-posteriori a set of most frequent responses to the questions 1 and 2 (see the table below, Figure 15). For the third question, there were only two possible answers; subjects could either point at the square or at the rectangle. For questions 1 and 2, answers' frequencies were computed for each subject; subjects were given a score of 1 or 0 for each possible response (post-test score). For the third question, subjects were given a score of 1 if they got it correct twice (if they pointed twice at the rectangle), both if the drawing was oriented vertically or horizontally. They got a 0 score if they got it wrong twice or if they got it only correct once. Results were analyzed separately for Experiment 1 for each age group (discontinuous boundaries, Figure 15a), on the one hand, and Experiment 2 for each age group (continuous boundaries, Figure 15b) on the other hand. In order to investigate whether the perception of the arena's shape and walls was related to the children's performance at the reorientation task, we analyzed correlations between children's performances at the reorientation task (C+G proportion) and the post-test score they got for the first, the second and the third post-test question (see the table below). For Experiment 1, we found a significant correlation between the performance at the reorientation task and question 3 ($r=0.33$; $p=0.015$). For Experiment 2 we didn't find any significant correlation.

Table 1

***Table 1a**. Correlations of children's performance in the reorientation task (C+G) and children's post-test scores for each response to Question 1: "In this room there is a shape, can you tell me which one?".*

C+G	Experiment	Rectangle	Square	Circle	Prism	None
4-6 years old	Exp.1	-.196	.224	-.149	-.017	-.006
	Exp. 2	-.192	.034	.012	-	-.082
7-9 years old	Exp.1	-.020	-.116	.069	.097	.158
	Exp. 2	.007	.137	-0.31	-.021	-.119

*= the correlation is significant at the level 0.05 (2-tailed).

**=the correlation is significant at the level 0.01 (2-tailed).

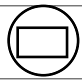
Table 1b. *Correlations of children's performance in the reorientation task (C+G) and children's post-test scores for each response to Question 2: "How many walls do you see?".*

C+G	Experiment	4 walls	1 wall	20 walls	None
4-6 years old	Exp.1	.169	-	-.331	-.006
	Exp. 2	-.109	.208	.094	-.109
7-9 years old	Exp.1	-.123	-.025	.073	.065
	Exp. 2	-.188	.110	-.122	.205

*= the correlation is significant at the level 0.05 (2-tailed).

**=the correlation is significant at the level 0.01 (2-tailed).

Table 1c. *Correlations of children's performance in the reorientation task (C+G) and children's post-test scores for each response to Question 2: "How many walls do you see?".*

C+G	Experiment	Correct	
4-6 years old	Exp.1	.470*	
	Exp. 2	-.177	
7-9 years old	Exp.1	.050	
	Exp. 2	.205	

*= the correlation is significant at the level 0.05 (2-tailed).

**=the correlation is significant at the level 0.01 (2-tailed).

Figure 15. 1a) The table presents Pearson correlations of children's performances at the reorientation task (C+G, correct + geometrically correct choices) averaged across age groups and the post-test score (see Paragraph 9) for each response at the post-test question 1 in Experiment 1 (continuous boundaries) and 2 (discontinuous boundaries). 1b) The table

presents Pearson correlations of children's performances at the reorientation task (C+G, correct + geometrically correct choices) averaged across age groups and the post-test score (see Paragraph 9) for each response at the post-test question 2, in Experiment 1 and 2. 1c) The table presents Pearson correlations of children's performances at the reorientation task (C+G, correct + geometrically correct choices) averaged across age groups and the post-test score (see Paragraph 9) for each response at the post-test question 3, in Experiment 1 and 2.

Discussion

In this study we set out to gain insight into the role of geometric configurations of objects in children's ability to represent space for navigation. Indeed, previous studies have shown that children are able to use boundaries as long as they are continuous and extended and failed when boundaries were made up of discrete objects. However, from those studies, it wasn't clear whether children failed the task because, on the one hand, the arrays made up of discrete objects were not sufficiently dense to prevent movement or to underline the geometric structure or, on the other hand, because the boundaries made up of objects are processed differently from continuous and extended boundaries and require specific cognitive mechanisms to activate. In our study, we wanted to answer these questions. Therefore, we further investigated children's use of a geometric configuration of objects in a reorientation task by testing them with an objects' array that was sufficiently dense to prevent movement and to clearly underline the geometric figure in order to be able to either confirm or to exclude possible accounts of children's failure.

To this aim, we tested children in a reorientation task both with discontinuous walls made up of objects with an inter-object distance of either 16 cm (Experiment 1, Condition 1) or 8 cm (Experiment 2, Condition 2), and with continuous walls, either four walls of 50 cm (Experiment 1, Condition 1) or two walls of 100 cm (Experiment 2, Condition 2). We found out that children didn't perform significantly above the level of chance in the Discontinuous Boundaries Experiment (Experiment 1) in the age group 4-6 years of age while they performed significantly above the level of chance in the age group 7-9 years of age. In contrast, children performed significantly above the level of chance in both age groups in the Continuous boundaries Experiment (Experiment 2). Additionally, the performances in the two Experiments differed significantly for the younger age group (4-6 years of age) but not for the older age group.

To sum up, we found out that while children remembered spatial locations with respect to continuous boundaries from the age of four, they reliably used discontinuous boundaries starting around the age of seven. Therefore, the two Experiments presented different developmental patterns: while a consistent developmental change was present in children's representation of discontinuous boundaries, children seemed to be able to use continuous boundaries equally at all ages.

Despite some limitations of our study due to the relatively small size of the sample that did not allow a full, in-depth data analysis, we can still try to draw initial, but nonetheless important, conclusions from our results.

These results are in line with previous studies showing children's difficulty in encoding the geometric shape of objects' configurations in order to reorient (Gouteux & Spelke 2001; Lee & Spelke 2008; 2011), and, conversely, children's capacity of using continuous, extended surfaces (Hermer & Spelke 1994; 1996; Lee & Spelke 2008).

As a first outcome of our Experiment, it is possible to exclude that the hypothesis we discussed in our Introduction that children failed in using configurations of objects, both in previous studies and in our study, because the arrays were not sufficiently dense to prevent movement or to underline the geometric structure. But why did children fail and acquire the capacity to process discontinuous boundaries so late?

Based on previous evidence concerning both spatial behavior of children and adults and its neural underpinnings, these results may be read in light of two possible interpretations. First of all, it is possible to argue that children's failure to use a configuration of objects to reorient is related to evidence from a variety of behavioral, neuro-imaging, and electrophysiological studies in animals showing that the use of objects and boundaries in navigation is mediated by different cognitive mechanisms, obeys distinct rules and involves different networks of the brain. Interestingly, as late developmental changes can be observed in our results, some of these studies have shown that for children up to a certain age, it is difficult to integrate these two cognitive mechanisms during navigation and that this integration occurs late in development. How did the different use of boundaries and objects in navigation affect our results? Let's first review the evidence on the use of features/objects and boundaries in navigation in humans.

Previous studies have shown that children can reliably use the rectangular shape of a layout in a reorientation task from the age of two. On a hiding and finding game in a rectangular chamber, after disorientation, they were shown to search for the hidden object in the correct corner and in the geometric equivalent corner with the same frequency. When corners were disambiguated by means of a colored panel covering one of the four chamber's walls, they ignored the feature for reorienting and still searched for the hidden toy in the correct and geometric equivalent corners. While children did not show the capacity of integrating featural and geometric information to solve the task, adults were shown to be able to correctly integrate featural and geometric information by searching for the hidden object mainly in the correct corner (Hermer & Spelke 1994; Hermer & Spelke 1996; Lee & Spelke 2010b). Some researchers hypothesized that the capacity of integrating featural and geometric information might arise with the acquisition of language (Hermer-Vazquez, Moffet & Munkholm 2001; Hermer-Vazquez, Spelke & Katsnelson 1999). They first demonstrated that children become able to integrate featural and geometric information around the age range of five to seven (Hermer-Vazquez, Moffet & Munkholm 2001) and secondly, that an interfering verbal task disrupted the performance of adults in the reorientation task such that they couldn't reliably conjoin featural and geometric information (Hermer-Vazquez, Spelke & Katsnelson 1999).

Neural studies in humans complemented behavioral evidence by showing a neural dissociation in the use of objects and boundary-geometry. Neural underpinnings of the use of feature/objects and geometry were studied in humans using fMRI (Doeller, King & Burgess 2008). In one study, subjects were scanned while performing a VR task in which they had to retrieve the position of an object with respect to either boundaries or objects present in the navigating scene. The study showed that learning a position of an object with respect to boundaries activated the hippocampus while learning the position of an object with respect to landmarks mostly activated the striatum (Doeller, King & Burgess 2008). Further behavioral studies showed that while the use of boundaries is based on an incidental, automatic capacity that is not subject to overshadowing, the use of landmark is mediated by a different cognitive process (associative reinforcement) that is acquired through cumulative training and is subject to interference from other memory tasks (Doeller & Burgess 2008). The use of objects and boundaries was further investigated in imagery of spatial scenes. A study showed that when subjects viewed a spatial configuration of enclosing, horizontally extended walls, the hippocampal activity was much higher that when subjects viewed a configuration of separated vertical objects. Moreover, the overall hippocampal activity was increasingly modulated by the number of enclosing boundaries and was not affected by other factors such as color or complexity of the imagined scene (Bird et al. 2010).

In line with the above-mentioned data, we can argue that 4-6-year-old children failed in our task because they were still not able to integrate different sources of information, namely boundaries' and objects' information. Indeed, it is possible that in our task both kinds of information were present. Information coming from the layout indicated the presence of a boundary and information coming from the discrete components of the boundaries indicated the presence of discrete objects in the navigating scene. Integrating boundaries' and objects' information might be particularly challenging in children since it requires to flexibly combine at least two distinct cognitive mechanisms, and to process information at a higher degree of abstraction. Consistently with this interpretation, the fact that children became able to use boundaries made up of objects at the age of seven may be in line with previous results we reviewed above (Hermer-Vazquez 2001), indicating that children overcome their inability to integrate information coming from boundaries and features around the age of five to seven.

Along the same line of interpretation, children's inability to use the objects might be, more simply, tied to their incapacity to process information coming from objects. This last interpretation might find support in behavioral navigation tasks showing that children start to use landmarks only around the age of seven and increase their capacity all the way until ten years of age (Lehnung et al. 1998).

Further behavioral studies analyzing the capacity of using landmarks in a reorientation task and further fMRI studies on the neural underpinnings of children's use of features and configurations of objects are needed in order to support these hypotheses.

On the other hand, it is possible to argue that children's failure to use object arrays is due to an immature hippocampal development. Indeed, some studies have shown that the use of pillars in a reorientation task requires much hippocampal activity and importantly, the literature shows that full hippocampal development in children is not seen until the age of 8 or 9. Sutton, Joanisse and Newcombe (2010) scanned a group of adults while they were performing a reorientation task in three different conditions: in a rectangular chamber with no features, in a rectangular chamber with a red panel attached on a wall and in a square chamber with a red panel attached on a wall. They found out that hippocampal activity was greater in the second and third condition with respect to the first condition and interpreted this data by arguing that the use of features requires more hippocampal activation. Similarly, they tested adults in a virtual reorientation task in three conditions: a rectangular configuration made up of four walls, a rectangular configuration made up of four pillars (resembling those used in Lee et al. 2008) and a rectangular configuration made up of a flat mat (again resembling the 2D shape used in Lee et al. 2008). They found more hippocampal activation in the pillars' condition with respect to the other two conditions. They thus argued that processing objects' configurations mostly requires hippocampal activity. On the basis of these findings, they hypothesized that children failed in using a configuration of objects in previous studies because of an immature hippocampal development. They also based their hypotheses on evidence that showed that hippocampal development protracts until the age of 8 or 9 (Alvarado & Bachevalier 2000; Gogtay et al. 2006; Utsunomiya et al. 1999). Similarly, the failure in children of 4-6 years of age in our study might reflect an immature hippocampal development. Further studies on the neural underpinnings of children use of objects-configurations are needed to solve this issue.

Interestingly, the result of our post-tests (the correlation we found between children's representation of the apparatus and their performance), are compatible with both interpretations of our data. The results showed that as long as children correctly solved the reorientation task, their representation of the apparatus resembled a rectangle. In contrast, these results showed that children's mental representation of the apparatus, as long as they failed the reorientation task, resembled a square. It is thus possible that the configuration of objects prevented children's perception of the difference in length and/or distance of the walls (in Chapter 3 we tried to investigate whether children relied on distance estimation or length estimation in order to solve the reorientation task). In line with this interpretation it is possible to argue that objects made the geometric configuration either more difficult or even impossible for children to detect.

Considering Experiment 2, it is worth mentioning that the results (Condition 1 and 2) are in line with studies showing that children can use continuous, extended boundaries in navigation. Indeed, we have shown that they succeeded in Experiment 2 in both Conditions. Nonetheless, in our study, particularly in Experiment 2, in order to understand what kind of properties a boundary should have in order to be used in navigation by children, we were interested in investigating at which boundary-length children start differentiating a boundary from a discrete object, particularly because previous studies found that objects and boundaries constitute qualitatively different stimuli in navigation. To this aim, as in previous studies, the minimal surface length tested was 80 cm (Gianni, De Zorzi & Lee 2018) we tested children with an even shorter surface (50 cm). If children considered a 50 cm boundary as a discrete object, we expected them to fail the task, as in previous studies it was shown children are not able to use single objects to reorient (Lee et al. 2006). If they still considered the surface to be a boundary, we expected them to succeed. However, this was the last case. Therefore, we can conclude that 50 cm is not yet the minimal length at which a boundary starts to be perceived as an object. Thus, in order to keep on with this study, it might be interesting to define the optimal length at which children perceive the boundaries as distinct from an object and start failing in the reorientation tasks by testing subjects with even shorter walls.

However, it is worth to mention that there might be another explanation underlying children's capacity to use 50 cm (or shorter) segmented boundaries. Indeed, the particular rectangular configuration could lead to a mechanism of completion, enabling them to perceive boundaries as continuous. In this line of interpretation it is possible to argue that not only the length, but also the degree of spacing of the boundaries between each other, might have affected children's perception of boundaries as continuous. At this point, the experimental question would be "Which boundary's length and which degree of spacing between the four boundaries enable children to complete the geometric shape and consider the boundaries as if they were continuous?" Nonetheless, if it is true that children activated a mechanism of amodal completion enabling them to perceive the 50cm walls as continuous, it might also be interesting in future studies to come up with experimental apparatuses that test different boundary lengths by contemporary preventing mechanisms of amodal completion. The apparatus we used in Chapter 3, made up of only two surfaces, might be ideal to test children in an eventual future task (see Chapter 3, Introduction).

For the future, it is still important to increase the sample size in in Experiment 1 and in Experiment 2. In order to reach a power of 0.8, if we want to make Experiment 1 (discontinuous boundaries) and Experiment 2 (continuous boundaries) results fully comparable across age groups, we computed that 119 subjects in each one of the two Experiments would be needed. Increasing the sample size would reinforce our conclusions regarding the difference in performance between the two experiments, and also allow us to show possible significant interactions between the variable "age group" and the continuity/discontinuity condition.

Finally, as we noticed above, through our study we were able to show how the use of discontinuous boundaries made up of discrete objects and continuous boundaries followed different developmental patterns. Therefore, our study essentially contributes to the debate in the spatial navigation field by showing first, that young children are not able to use configuration of objects in navigation, confirming objects and boundaries in the navigable space to be qualitatively different and suggesting that their use in navigation might be mediated by different systems and second, it helped to exclude alternative accounts that explain children's inability to use configuration of objects as being because the arrays were not sufficiently dense to prevent movement or to underline the geometric structure. Moreover, our results show that the capacity of processing geometric configurations of objects arises late in development and that important changes may co-occur in children's spatial representation at that developmental stage.

References

Alvarado, M. C., & Bachevalier, J. (2000). Revisiting the maturation of medial temporal lobe memory functions in primates. *Learning & Memory*, *7*(5), 244-256.

Benhamou, S., & Poucet, B. (1998). Landmark use by navigating rats (Rattus norvegicus) contrasting geometric and featural information. *Journal of Comparative Psychology*, *112*(3), 317.

Bird, C. M., Capponi, C., King, J. A., Doeller, C. F., & Burgess, N. (2010). Establishing the boundaries: the hippocampal contribution to imagining scenes. *Journal of Neuroscience*, *30*(35), 11688-11695.

Burgess N. (2006). Spatial memory: How egocentric and allocentric combine. Trends in Cognitive Sciences.; 10:551–557.

Cheng, K. (1986). A purely geometric module in the rat's spatial representation. *Cognition*, *23*(2), 149-178.

Cressant, A., Muller, R. U., & Poucet, B. (1997). Failure of centrally placed objects to control the firing fields of hippocampal place cells. *Journal of Neuroscience*, *17*(7), 2531-2542.

Doeller, C. F., & Burgess, N. (2008). Distinct error-correcting and incidental learning of location relative to landmarks and boundaries. *Proceedings of the National Academy of Sciences*, *105*(15), 5909-5914.

Doeller, C. F., King, J. A., & Burgess, N. (2008). Parallel striatal and hippocampal systems for landmarks and boundaries in spatial memory. *Proceedings of the National Academy of Sciences*, *105*(15), 5915-5920.

Gianni, E., De Zorzi, L., & Lee, S. A. (2018). The developing role of transparent surfaces in children's spatial representation. *Cognitive Psychology*, *105*, 39-52.

Gogtay, N., Nugent III, T. F., Herman, D. H., Ordonez, A., Greenstein, D., Hayashi, K. M., ... & Thompson, P. M. (2006). Dynamic mapping of normal human hippocampal development. *Hippocampus*, *16*(8), 664-672.

Gouteux, S., & Spelke, E. S. (2001). Children's use of geometry and landmarks to reorient in an open space. *Cognition*, *81*(2), 119-148.

Hermer, L., & Spelke, E. S. (1994). A geometric process for spatial reorientation in young children. *Nature*, *370*(6484), 57.

Hermer, L., & Spelke, E. (1996). Modularity and development: The case of spatial reorientation. *Cognition*, *61*(3), 195-232.

Hermer-Vazquez, L., Spelke, E. S., & Katsnelson, A. S. (1999). Sources of flexibility in human cognition: Dual-task studies of space and language. *Cognitive psychology*, *39*(1), 3-36.

Hermer-Vazquez, L., Moffet, A., & Munkholm, P. (2001). Language, space, and the development of cognitive flexibility in humans: The case of two spatial memory tasks. *Cognition*, *79*(3), 263-299.

Kosslyn, S. M., Pick Jr, H. L., & Fariello, G. R. (1974). Cognitive maps in children and men. *Child development*, 707-716.

Lee, S. A., Shusterman, A., & Spelke, E. S. (2006). Reorientation and landmark-guided search by young children: Evidence for two systems. *Psychological Science*, *17*(7), 577-582.

Lee, S. A., Sovrano, V. A., & Spelke, E. S. (2012). Navigation as a source of geometric knowledge: Young children's use of length, angle, distance, and direction in a reorientation task. *Cognition*, *123*(1), 144-161.

Lee, S. A., & Spelke, E. S. (2008). Children's use of geometry for reorientation. *Developmental science*, *11*(5), 743-749.

Lee, S. A., & Spelke, E. S. (2010a). A modular geometric mechanism for reorientation in children. *Cognitive psychology*, *61*(2), 152-176.

Lee, S. A., & Spelke, E. S. (2010b). Two systems of spatial representation underlying navigation. *Experimental Brain Research*, *206*(2), 179-188.

Lee, S. A., & Spelke, E. S. (2011). Young children reorient by computing layout geometry, not by matching images of the environment. *Psychonomic bulletin & review*, *18*(1), 192-198.

Lehnung, M., Leplow, B., Friege, L., Herzog, A., Ferstl, R., & Mehdorn, M. (1998). Development of spatial memory and spatial orientation in preschoolers and primary school children. *British Journal of Psychology*, *89*(3), 463-480.

Lever, C., Wills, T., Cacucci, F., Burgess, N., & O'keefe, J. (2002). Long-term plasticity in hippocampal place-cell representation of environmental geometry. *Nature*, *416*(6876), 90-94.

Newcombe, N., & Liben, L. S. (1982). Barrier effects in the cognitive maps of children and adults. *Journal of Experimental Child Psychology*, *34*(1), 46-58.

O'Keefe, J. O., & Burgess, N. (1996). Geometric determinants of the place fields of hippocampal neurons. *Nature*, *381*(6581), 425.

Sutton, J. E., Joanisse, M. F., & Newcombe, N. S. (2010). Spinning in the scanner: Neural correlates of virtual reorientation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *36*(5), 1097.

Utsunomiya, H., Takano, K., Okazaki, M., & Mitsudome, A. (1999). Development of the temporal lobe in infants and children: analysis by MR-based volumetry. *American Journal of Neuroradiology*, *20*(4), 717-723.

Chapter 3

The geometric representation of boundary distance in navigation and map-use

Abstract

Past studies have reported that children from as early as the age of two are able to use the geometry of boundaries to orientate themselves. But Euclidean geometry can be divided into four fundamental properties: angle, distance, length and direction. Which geometric components of the boundaries are children most sensitive to? How does their use in spatial tasks change over development? The literature points to two different cognitive systems based on the use of Euclidean geometry: navigation and visual form analysis. Previous studies have shown that children can use distance and direction, but not length in navigation tasks, while they are able to use length in visual form analysis tasks, but not direction. Map studies have also been used to investigate children's use of Euclidean geometry, since map reading requires the competence to relate the analysis of geometric properties of the 3D navigable space with the analysis of geometric properties of visual forms on a bi-dimensional small-scale representation. Previous studies with maps showed that 2-year-old children can use length and distance information to solve a map placement task. However, these studies were limited, because the two properties were mixed and both available at once. Therefore, it is not really possible to infer whether distance or length (or even angle and sense information) were used to solve map tasks. Moreover, reorientation and map study results were not comparable, because they were obtained by testing children of different age ranges in different experimental conditions (using either different methodologies or different arrays). In our study, we started to investigate which geometric components underlie children's sensitivity to geometric layouts by carefully isolating the properties of distance and length. We tested children from 2.5 to 3.5 years old, both on a reorientation and on a map task, in the same experimental environment. Our results confirmed that children are able to use distance but not length in a reorientation task from 30 to 42 months old, and they suggested children are not able to use distance or length in a map task.

1. Introduction

1.1 Reorientation task

In order to investigate which properties of the environment are stored by animals while navigating, researchers have used the reorientation task. In this task, a reward is hidden in a particular location, then the subject is disoriented as far as to lose track of the direction it was heading in and its position. The subject is then asked to find the hidden reward. This paradigm allowed researchers to figure out which characteristics of the environment subjects tend to rely on in order to remember their previous position and to find the reward's location. Thus, researchers used this paradigm in order to investigate the properties of the animals' and humans' spatial maps. The first reorientation study was conducted by Cheng (1986) in rats. Hungry rats were placed in a rectangular arena and trained to visit a particular corner where food was placed. Subsequently, the rats were disoriented, and the food was buried at the target corner. While rats were replaced in the rectangular arena searching for the food, the researcher observed that they visited the target corner and its geometric equivalent with the same frequency, demonstrating an ability to reorient according to the shape of the environmental layout. When the two geometrically equivalent corners were disambiguated by odors or colored panels, rats still tended to visit the two geometrically equivalent corners and to ignore the presence of the features (see also the General Introduction, paragraph 3 for a more extensive description of this paradigm).

Children, as young as two years old, were also tested in a reorientation task (Hermer & Spelke, 1994; 1996) in a rectangular chamber. They were shown the location of a hidden object (usually a toy) in a target corner and subsequently disoriented. The study showed that children, as well as rats, tended to visit the correct and geometrically equivalent corners with the same frequency, showing they were able to use the geometric properties of the layout to reorient. When the two geometrically equivalent corners were disambiguated by means of a colored panel, children still tended to visit the two geometrically equivalent corners, suggesting they are insensitive to spatial cues other than the geometric shape of the layout. The same reorientation behavior was observed in other animals like ants (Wystrach & Beugnon 2009), chicks (Lee et al 2012) and zebrafish (Lee et al. 2013). Not only were children shown to be able to reorient according to the rectangular shape of the environment, but also if the geometric shape was triangular (Lourenco & Huttenlocher 2006; Huttenlocher et al. 2008), rhombic (Hupbach & Nadel 2005) and octagonal (Newcombe et al. 2010).

Euclidean geometry is based on different components: distance, direction (or sense), angle and length. Which components do children use to solve the reorientation task? From the studies we mentioned above it is not possible to infer exactly which properties children used because distance, direction, angle and length information were mixed and all available at once in triangular, rhombic, octagonal and rectangular arrangements. For example, in order to solve the reorientation task in a rectangular chamber, children might rely either on the difference in length between two adjacent sides, combined with a sense of left and right (both the target and the geometric equivalent corners are indeed characterized by a short wall on the left and a long wall on the right, or the opposite); or on an estimation of the distance between the subject's position and the walls (two walls are closer to the subjects and two walls are farther) combined with sense; or finally on an estimation of the relative distances between the walls themselves (two walls are closer to each other and two walls are farther) combined with sense. Similarly, in the rhombic environment, children might use both the difference in amplitude between the two corners and the distance of the corners from the subject's position or even the relative distances between the two couples of corners.

In 2012, Lee et al. conducted a study in which they disentangled distance, direction, length and angle information by testing children of two years of age with segmented arrays (Figure 16). In experiment 1 and 2 (rhombic arrays with continuous walls), children reoriented correctly by visiting the correct corner and the geometrically equivalent corner with the same frequency. In these two experiments, distance and angle information were mixed making it difficult to understand which of the two geometric properties children relied mostly on. Experiment 3 and 4 were designed in order to understand whether children were able to use angle information. To this aim, four fragmented angles were used to form an array by keeping distance and length constant. In these two experiments, children were unable to reorient correctly, suggesting that angle information alone was not sufficient to guide their reorientation behavior. Experiment 5 and 6 tested children's use of distance and angle information in fragmented arrays. In Experiment 5, children were tested in a rhombic array with four fragmented angles at a different distance to each other. Children failed this task, being unable to use the difference in distance or amplitude between the two pairs of angles in order to reorient. In Experiment 6, children were tested in a rhombic environment with four fragmented surfaces. They succeeded in the task, showing they were able to rely on the distance information alone to reorient. Experiment 7 isolated length information while keeping distance and angle information constant using four fragmented surfaces of different lengths. In this experiment, children failed at the reorientation task, suggesting length information alone was not sufficient to guide their reorientation behavior. Finally, Experiment 8 isolated distance information while keeping angle and length information constant by testing children with four fragmented surfaces placed at different distances from each other and at a different distance from the center. Children demonstrated they were able to reorient correctly in this last experiment, suggesting that distance information (in combination with sense) is sufficient to guide their reorientation behavior. From this study the authors concluded that children could use distance and direction to orient, but not angle and length.

	Proportion of geometric searches	Success?
Exp. 1	0.73	Yes
Exp. 2	0.70	Yes
Exp. 3	0.56	No
Exp. 4	0.54	No
Exp. 5	0.45	No
Exp. 6	0.69	Yes
Exp.7	0.45	No
Exp. 8	0.69	Yes

Figure 16. The table presents the arrays used in Lee et al. 2012, the proportion of geometric choices in each array and their success/failure. Published with permission of the authors.

Yousif and Lourenco (2017) recently carried out different results that posed a challenge to Lee and Spelke's conclusions, in particular to the assumption of children's exclusive ability to use distance but not length. First of all, they assumed that children's inability to use the length property was due to the characteristics of the array used in this experiment. Indeed (see from the figure above (exp. 7)), the length condition had four segmented borders of different length but arranged in a squared fashion, while in the distance condition the authors used four borders of equal length but arranged in a rectangular fashion (exp. 8). Yousif and Lourenco hypothesized children could not use the square shaped array, even if provided with a visible length difference between its borders because they tended to neglect the length difference due to a mechanism of perceptual completion (i.e. the tendency to perceive the segmented borders as if they were continuous), prompting them to infer the array's global shape and to reorient according to it. The evidence put forth to make this claim involved presenting children with four panels of different lengths, at which extremities they put perpendicular panels in order to prevent children from activating a completion mechanism. They showed that children were able to use the length difference to reorient in this particular condition, and they concluded children are able to use both distance and length in order to solve the reorientation task.

Nevertheless, not only did the researchers fail to explain why children didn't succeed by using amodal completion in the angle condition in the experiment by Lee et al. 2012, but also, by putting perpendicular panels in the length condition, they underlined the difference in distance of the two end-panels to the corners of the array, thereby confusing the distance and length condition. Similarly, they missed explaining whether in the distance condition, when the panels were arranged in a rectangular shape, children solved the task by amodally completing the array based on the length difference between the borders, or based on the difference in distance. Since distance and length conditions were not correctly disentangled, the question of which geometric properties children used in order to solve the reorientation task remained unanswered. In particular, are young children able to solve the reorientation task by using length, distance or by a mix of the two properties?

In order to address those issues, we carefully isolated the distance and length conditions by using a two-borders array in our experiment. The two-borders array prevented children completing the geometric form of the array and solving the task by inferring its global shape, making it possible to establish with certainty whether children use distance or length (or both) to solve the reorientation task.

Moreover, behavioral studies with animals suggested that rodents, as well as children, can solve the reorientation task in a rectangular arena (Cheng 1986) and neural studies suggested that they can move and orient by computing distance and directions from the walls (O'Keefe & Burgess 1996, see also the General Introduction). Which kind of mechanisms enable children to reorient? Are the same mechanisms activated in children also?

By isolating distance and length information in a reorientation task with young children, we started answering this fundamental question, at least from a behavioral point of view.

1.2 Map task

The literature points to two different competences (navigation and visual form analysis) related to the use of Euclidean geometry (Spelke et al. 2010). So far, it was shown that children can use angle and length information in 2D visual form analysis, but not sense information. This capacity is spread throughout different cultures (Dehaene et al. 2006) and the difficulty of using sense is protracted until adolescence. On the other hand, children were shown to be able to use distance and sense information, but not angle and length information in order to navigate in 3D environments. These studies suggest that there might be different cognitive mechanisms supporting navigation, on the one hand, and visual form analysis on the other hand. Each mechanism might have its own developmental trajectory.

Map-use studies turn out to be particularly interesting tools to study these two systems, since map reading requires the children to identify a relationship the geometric characteristics of the 3D environment and the geometric characteristics they perceive on the small-scale representation (the map), resulting in a more abstract geometric knowledge. Map studies were so far conducted by using placement tasks, in which the child is required to place a toy in a location which is pointed to on a map by the experimenter. These studies have shown that children acquire the competence to read maps from a very early age (Huttenlocher et al. 1999; Vasilyeva & Bowers 2006; Winkler-Rhoades et al. 2013, Spelke et al. 2011, Dillon et al. 2013). However, previous studies presented some important limitations. As in reorientation studies, the different properties of Euclidean geometry (distance, angle, length, sense) were mixed and all available at once, making it difficult to understand which properties the children relied on in order to solve the map task.

Shusterman et al. (2008) tested children in a map task and showed that 4-year-old children were not able to use sense information in order to detect the difference between the two base corners of an isosceles triangle, but they correctly used distance (or length) and angle information to solve the task with a right triangle. Furthermore, they correctly used distance information in a linear object configuration. Similarly, Whinkler Rhoades et al. (2013) tested 2-year-old children in a triangular environment and showed they were able to solve the task when presented with an isosceles triangle by using angle and distance (or length) information. In these experiments, the distance, angle and length information were mixed.

In general, triangular arrays are not the best way to test map competences in children because information about angle, distance and length are correlated in these arrays. In order to circumvent this problem, Spelke et al. (2011) tested 5-year-old children in L-shaped arrays. Children were shown a map of the array and they had to decide which one matched the map between two different 3D arrays, differing either in distance, angle or sense. They found out that children were able to use distance and angle information in order to solve the task. However, the distance condition was tested using walls of different lengths, making it unclear whether children used distance or the length in order to solve the task.

Dillon et al. (2013) tested 4-year-old children with fragmented arrays arranged as a right triangle of either three fragmented angles (angle map task) or three surfaces (distance map task). They showed children were able to use both angle and distance information to solve the task. Here again, the components of Euclidean geometry children used to solve the task were difficult to distinguish. In the angle map task, children might have relied on the inferred distance or length between the sides of the imputed triangle, or by estimating the size-difference of the two corner angles themselves. In the distance map task, children might have relied on the relative distance between the triangle's sides or they might have chosen a location by estimating its distance from themselves.

Among these studies, the Izard et al. (2014) study was slightly different because the authors succeeded in isolating the angle property by testing children, with 3D triangular arrays and 2D maps representing only angle sections devoid of distance and length information. They showed that children succeeded in using maps from the age of four suggesting they reliably use the property angle when it is isolated from other information.

In conclusion, children have been shown to be able to reliably use distance and sense information in reorientation tasks, but not angle and length. Yet, they have been shown to be able to use length (or distance) and angle, but not sense information in 2D visual form analysis and in map tasks. Even if these studies are important to shed light on the fact that children presumably recruit different cognitive systems in order to solve spatial tasks (navigation tasks, visual form analysis and map tasks respectively), it is difficult to compare them. Such a difficulty stems from three main reasons: firstly, these studies recruited different groups of children, secondly, children tested in reorientation tasks were slightly younger than children tested in map tasks, and thirdly, map tasks often used triangular arrays, while reorientation tasks used rectangular arrays. Moreover, by focusing on a limited age range, these studies neglected to show how the capacity of using the Euclidean components arose and changed during development.

Which kind of geometric properties do children use in order to solve the map task? Does the ability to solve reorientation and map tasks present different developmental trajectories? If this is true are these two abilities mediated by different cognitive systems responding to different geometric properties?

In our study, we tried to start answering these questions and to overcome the limitations of the previous studies we discussed above. We tested the same group of children, aged 30 to 42 months, both in a reorientation and in a map-placement task, taking care to isolate the two geometric components of distance and length by using fragmented arrays composed of only two surfaces. Moreover, basing on previous evidence showing children's success in using angles in a map-task, we designed our control task and tested children 30 to 42 months old children in a similar map task also with angles. We focused here on a younger age range, with respect to the previous study, in order to make the map tasks comparable.

So far, this is the first study directly comparing the use of distance, length and angle in children aged 30 to 42 months. Indeed, most of the map studies we reviewed above, focused on slightly older age ranges and mixed the properties of length, distance and angle. However, we disentangled the three properties and chose to focus on such an early age range because two years is the age children become able to solve the reorientation task (Hermer & Spelke, 1994; 1996), and therefore, it becomes particularly interesting to start investigating which geometric properties children employ to solve the map task from this early age onwards. We also did this in order to make the two tasks (reorientation and map tasks) comparable.

2. Methods

2.1 Participants

Participants were made up of 32 children aged 30 to 42 months of age (Mean=35.91; SD=3.97) who were recruited from daycares and recreational centers in and around Paris, France. The participants were randomly split and tested either in length or distance conditions. Each participant was tested both in the reorientation and map tasks, and in the same condition (either length or distance). Two children were omitted from the dataset because they didn't complete the task. Informed consent from the parent or guardian and verbal consent from the child were obtained prior to the study.

2.2 Experimental Setting

Experiments were conducted within a windowless, soundproof room of the laboratory. Inside the room was placed a uniformly grey square tent of 285 cm long and 2 m high walls. The side of the tent facing the room's door had an opening that served as the entrance, and the floor was a uniform light-grey color. Once closed, the opening was made invisible (by accurately closing the tent) in order not to provide any external cue. The experiment was recorded through a hidden video camera hung from the center of the ceiling of the testing room. Inside the tent were placed two 50 cm high plain white plastic surfaces. The shape and position of the surfaces differed for each condition (Figure 17a-b). In the distance condition, we had two parallel straight surfaces of the same length positioned at a different distance from the center of the array with a ratio of 1:2 (Figure 17a).

It is worth noticing that in this condition, in contrast to past studies (Lee et al. 2012; Yousif & Lourenco 2017), we prevented a process of amodal completion of the boundaries' layout by providing contrasting distance information not between the surfaces themselves, but between the surfaces and the larger boundaries of the room (or even the surfaces and the subject) using an off-centered array.

In the length condition the two parallel, straight surfaces had the same distance from the center and from the tent, but differed in length with a ratio of 1:2 (Figure 17b). In front of each surface a grey inverted cup was placed, which served as a hiding place for the stickers in the reorientation task. In the map task, the cups had the same positions, but were not inverted and served as a hiding place for the small toy.

a) b)

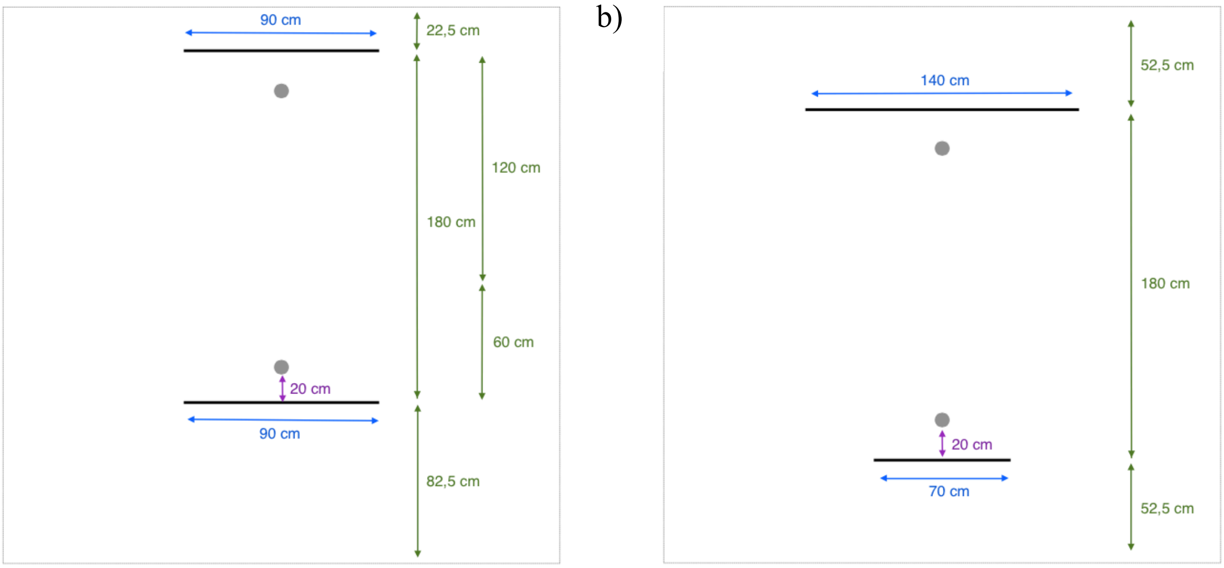


Figure 17. a) Schematic drawing of the array used in the "distance condition", view from above. By using this array it is impossible to amodally complete the geometric configuration, and, differing from past studies, the contrasting distance information is not provided by the difference in distance between the surfaces themselves, but by the difference in distance between the surfaces and the larger boundaries of the room (or between the surfaces and the subject), thanks to the use of an off-centered array. b) Schematic drawing of the array used in the "length condition", view from above. Pictures taken from Anna Gui's Master thesis (2015) with permission of the author.

2.3 Maps

The maps were 16 drawings of the arrays on a 20x20 cm squared cartoon sheet. There were eight maps for each array, representing the two possible locations of the target combined with the four possible orientations of the map. The maps represented the arrays and the surrounding environment at a 1:20 scale. The target location was indicated by a light blue star (Figure 18), while the surfaces were represented by means of black lines.

a) b)

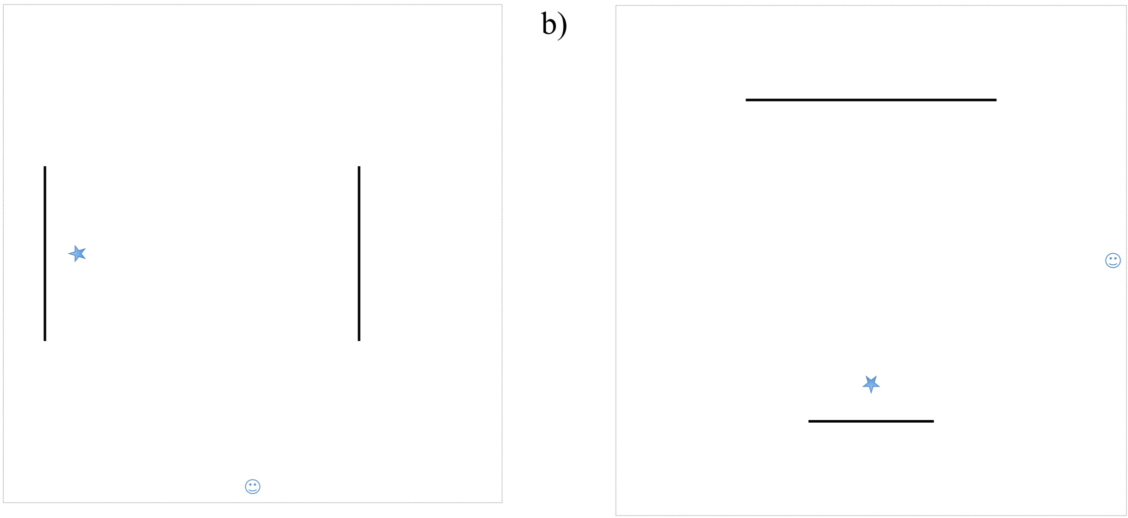


Figure 18. a) Example of one map presented in the "distance condition", orientation: 1, target in position: b. b) Example of one map presented in the "length condition", orientation: 3, target position: b. Pictures taken from Anna Gui's Master thesis (2015) with permission of the author.

2.4 Design

2.4.1 Reorientation task

Children were tested on four separate trials with the target position in the same location and were motivated by rewarding them with a sticker every time they found it. Equal numbers of children were tested with each position as the target. The direction in which children faced at the end of the disorientation procedure (one of the four sides of the squared tent) was varied across trials and counterbalanced across participants. To assess the use of the spatial information provided by the environmental layout, the total proportion of correct first choices on four trials was computed for each subject (subjects could get a score ranging from 0 to 1). Scores were averaged across subjects for every condition. T-tests against the level of chance were used to investigate children's performance in every condition. An ANOVA with sex and geometric condition as between-subjects variables was used to investigate difference in performance across conditions.

2.4.2 Map task

Children were tested on four separate trials (one per facing direction of the child, where facing directions corresponded to the four different sides of the tent), and three factors were varied across trials: the facing direction, the target positions and the orientation of the maps. Facing directions were varied across trials and counterbalanced across subjects. The target positions changed across trials and were counterbalanced across subjects. Each child was tested with four different map orientations and the order of map orientations was counterbalanced across subjects. To assess the use of the spatial information provided by the environmental layout, the total proportion of correct first choices on four trials was computed for each subject (subjects could get a score ranging from 0 to 1). Scores were averaged across subjects for every condition. T-tests against the level of chance were used to investigate children's performance in every condition. An ANOVA with sex and geometric condition as between-subjects variables was used to investigate difference in performance across conditions.

2.5 Experimental Procedures

The experiment was composed of two tasks: a reorientation task and a map task. As required by the Ethical Committee, the parent was invited to enter the experimental room. They were required to hold the child in their arms during the disorientation trial and were asked to take care not to give any clue about the position of the target during the whole experiment.

2.5.1 Reorientation task

Before playing the game, children were instructed that they were about to play a hiding and finding game accompanied by the parent and experimenter. Then the experimenter explained to the parents the procedure and their role in it. Before entering the testing room, the children were given a training trial in which the experimenter hid a sticker under a cup outside of the testing room and they had to pick it up. Once inside the testing room, each trial started with the parent and the child staying at the center of the array watching the experimenter hiding a sticker under one of the two cups. Then the parent picked up the child while covering the child's eyes with their hands and rotating for three or four times. The experimenter rotated around the children and counted to ten. She stopped on the side of the tent at the predetermined facing direction for that trial. The parent released the children in front of the experimenter and the children were encouraged to find the sticker. If they found it, then they were rewarded with the sticker. If they didn't find it, the experimenter showed the correct location. This procedure was repeated for four trials.

2.5.2 Map task

Before playing the game, the children were instructed that they were about to play a placement task in which they had to locate a rabbit in a position it preferred. While staying in the testing room, just after the reorientation experiment, the children were given a trial in order to check if they understood the procedure correctly. In this trial, the children were facing the array while standing with the experimenter along one side of the tent. The parent was close to the children's position. In this trial, a cup was placed at the center of the array and a map was shown to the children with the target-star placed at the center of the 2D array. Before starting the trial, the experimenter stressed the correspondence of the maps to the 3D environment by pointing to the borders of the array first in the map and then in the environment. Successively, the child was asked to place the rabbit in the position indicated by the star on the map. After this training trial, the cup at the center of the array was removed by the experimenter and children were tested on four consecutive trials, each one with a different facing direction. In these trials, the experimenter showed the map (maps varied in orientation), pointed to the star, which was located in either one or the other possible target positions, and asked the children to locate the rabbit in the environment in the place indicated by the star. Differing from the training trial, the children were turned while watching the map such that they faced the tent's walls and so that the 2D and 3D arrays were not possible to be seen together. In this task, children were given no feedback and the experimenter didn't show the correct position on incorrect trials.

3. Experimental Design

In order to investigate the capacity of navigating by distance and length in reorientation and map tasks, children from 30 to 42 months were tested with fragmented arrays, arranged to either isolate distance or length information. Two different groups of children were tested in the two conditions (distance and length). Each child was tested both in a reorientation and in a map task.

4. Results

4.1 Reorientation task

A univariate ANOVA with between-subjects variables condition and sex was used to investigate differences in performance across sexes and conditions. The results revealed there was no effect of sex ($F(3,28)=0.14$; $p=0.70$) but a significant effect of condition ($F=(3,28)=11.57$; $p=0.002$).

Given the discrete nature of the variables under analysis (i.e. in four trials, the correct searches are not continuous), we confirmed these findings by comparing performance across conditions using non-parametric statistics (Mann-Whitney $U = 52, p = 0.003$).

One-sample t-tests were used to compare the children's proportion of correct choices to the chance level (0.5). They revealed that children performed significantly above the level of chance in the distance condition ($t(15)=5.65$; $p<0.001$, Bonferroni corrected), but not in the length condition ($t(15)=1.14$; $p=0.54$, Bonferroni corrected).

In order to further investigate the results, children were divided into two age groups: 30 to 35 months (2.5 to 2.9 years) and 36 to 42 months (3 to 3.5 years). One-sample t-tests against the level of chance (0.5) showed that both younger and older children performed significantly above the level of chance in the distance condition (younger, $t(6)=3.28$; $p=0.034$, Bonferroni corrected; older, $t(8)=4.43$; $p=0.004$, Bonferroni corrected), but not in the length condition (younger, $t(6)=1$; $p=0.70$, Bonferroni corrected; older, $t(8)=0.47$; $p=1$, Bonferroni corrected).

In order to check for the effect of the training, paired-sample t-tests were used to compare the performance in the first two trials with the performance of the last two trials. The results didn't show any significant difference.

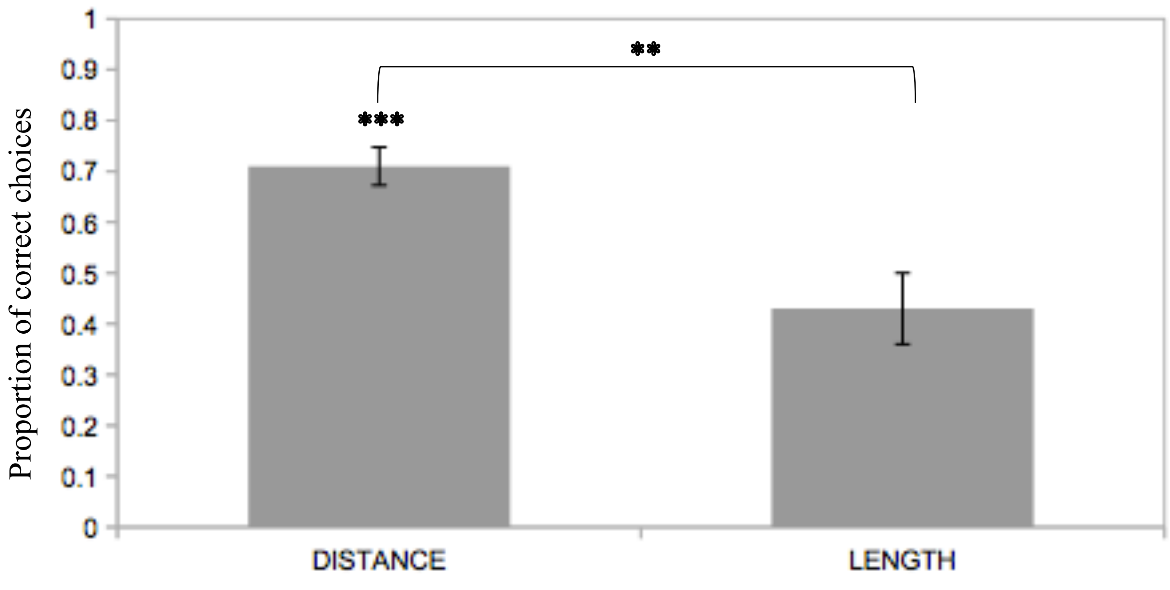


Figure 19. Proportion of correct choices averaged across subjects in the distance condition and in the length condition. *=p<0.05, **=p<0.01, ***=p<0.001.

4.2 Map task

A univariate ANOVA with between-subjects variables of condition and sex was used to investigate differences in performance across sex and condition. The results revealed no significant effect of sex ($F(3, 28)=0.66$; $p=0.42$), and no significant effect of condition ($F(3,28)=0.66$; $p=0.42$). Given the discrete nature of the variables under analysis (i.e. in four trials, the correct searches are not continuous), we confirmed these findings by comparing performance across conditions using non-parametric statistics (Mann-Whitney $U = 108, p = 0.468$).

One-sample t-tests were used to compare children's performances in the two separate conditions to the level of chance (0.5). They revealed children's performance was not different from the level of chance in the distance condition ($t(15)=0.56$; $p=1$, Bonferroni corrected) and in the length condition ($t(15)=0.62$; $p=1$, Bonferroni corrected).

In order to further investigate the results, children were divided into two age groups: 30 to 35 months (2.5 to 2.9 years) and 36 to 42 months (3 to 3.5 years). One-sample t-tests against the level of chance (0.5) showed that both younger and older children did not perform significantly above the level of chance in the distance condition (younger, $t(6)=0$; $p=1$, Bonferroni corrected; older $t(8)=0.61$; $p=1$, Bonferroni corrected) and in the length condition (younger, $t(6)=0$, $p=1$, Bonferroni corrected; older, $t(8)=1$; $p=0.68$, Bonferroni corrected).

In order to check for the effect of training, paired-sample t-tests were used to compare the performance in the first two trials with the performance of the last two trials. The results didn't show any significant difference.

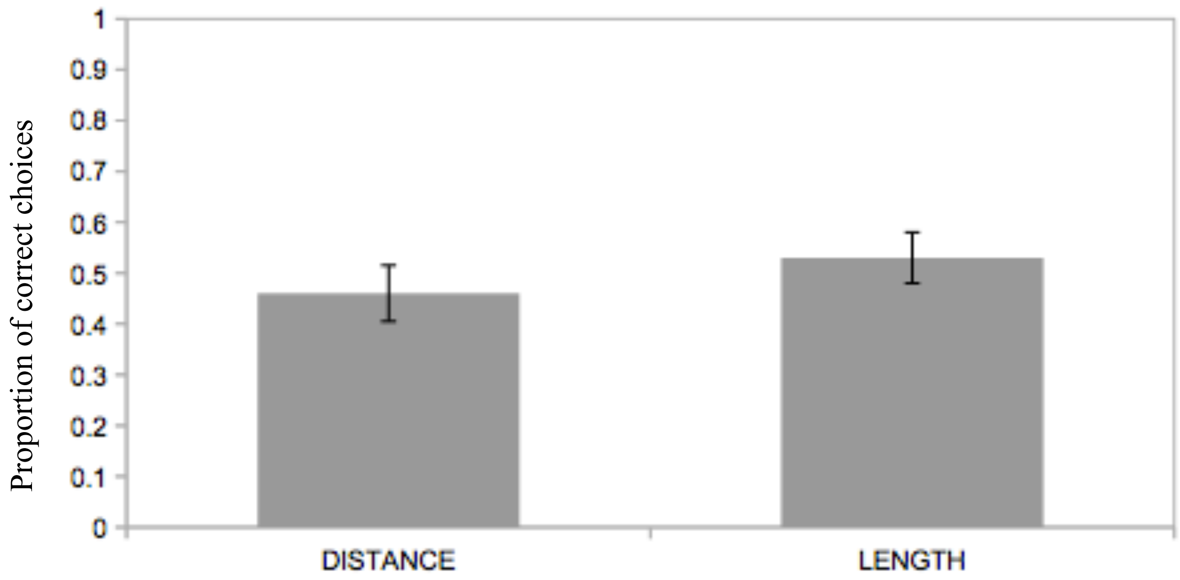


Figure 20. Proportion of correct choices averaged across subjects in the distance condition and in the length condition. Both conditions resulted in chance performance.

4.3 Reorientation and map tasks

A repeated measures ANOVA with between subjects variable condition (either distance or length) and within subjects variable task (either reorientation or map) was used to investigate differences in performance in the two tasks across conditions. The results showed no effect of task ($F(1, 30)=1.88$; $p=0.18$), a significant effect of condition $F(1,30)=4.29$; $p=0.047$ and a significant interaction of the two variables task and condition ($F(1,30)= 9.12$; $p=0.005$). This interaction was further explored using pair-wise post-hoc t-tests. The results revealed a significant difference across the two tasks (reorientation and map) in the distance condition ($t(15)=3.65$; $p=0.004$, Bonferroni corrected) and no significant difference for the length condition ($t(15)=1.03$; $p=0.62$, Bonferroni corrected). These findings were confirmed by using non-parametric statistics: distance, Mann-Whitney $U = 494$, $p = 0.006$; length: Mann-Whitney $U = 49$, $p = 0.688$).

A correlation analysis was used to compute the linear relation between the reorientation task and the map task. The results did not show any significant correlation for the whole group of children tested ($r=-0.14$; $p=0.43$), nor for the performances of children split by condition (distance, $r=-.30$; $p=0.91$; length, $r=-.11$; $p=0.68$).

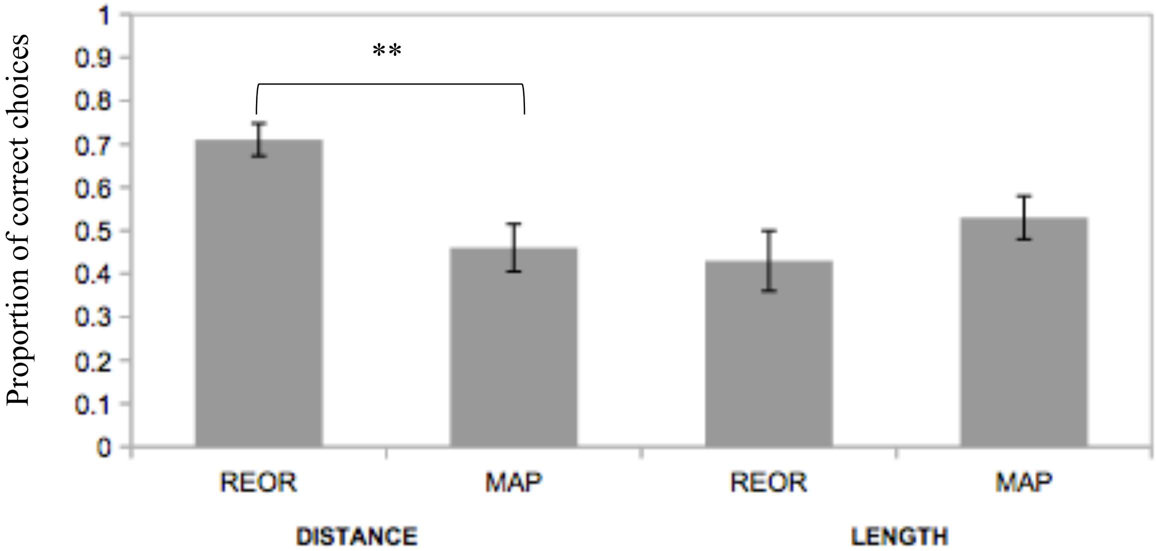


Figure 21. Proportion of correct choices averaged across subjects in the distance condition and in the length condition, for both reorientation and map tasks. *=p<0.05, **=p<0.01, ***=p<0.001.

8. Control Experiment: the use of angle in maps

8.1 Participants

In our control experiment participants were 16 children aged 30 to 42 months of age (*Mean*=35.81, *S*D=3.44) who were recruited from daycares and recreational centers in and around Paris, France. Each participated in a map task, in only one condition: the angle condition. Two children were omitted from the dataset because they didn't complete the task. Informed consent from the parent or guardian and verbal consent from the child were obtained prior to the study.

8.2 Experimental Setting

Experiments were conducted within a windowless, soundproof room of the laboratory. Inside the room was placed a uniformly grey square tent of 285 cm long and 2 m high walls. The side of the tent facing the room door had an opening that served as the entrance, and the floor was a uniform light-grey color. Once closed, the opening was made invisible (by accurately closing the tent) in order not to provide any external cue. The experiment was recorded through a hidden video camera hanging from the center of the ceiling of the testing room. Inside the tent were placed two 50 cm high plain white plastic surfaces. The surfaces were arranged as to form two angles of different amplitudes with the vertexes facing the tent. The ratio between the amplitudes of the two angles was 1:2 (the angles were 60 and 120 degrees, respectively). In front of each surface a grey cup was placed, and it served as hiding place for the toy in the map task.

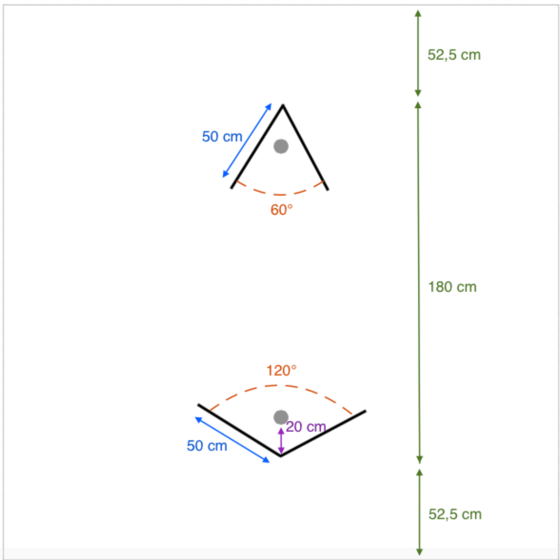


Figure 22. Schematic drawing of the array used in the Control Experiment, view from above.

8.3 Maps

The maps were eight drawings of the array on a 20x20 cm squared cartoon sheets. Each map represented one of the two possible locations of the target combined with the four possible orientations of the map. The maps represented the array and the surrounding environment at a 1:20 scale. The target location was indicated by a light blue star (Figure 23) while the surfaces were represented by means of black lines.

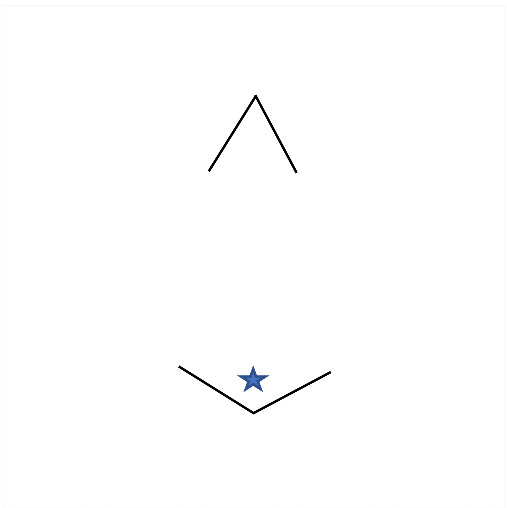


Figure 23. Example of one map used in Experiment 2. Orientation: 3, target position: b.

8.4 Experimental Procedures

Experimental procedures were the same as in the preceding Experiment (map task).

9. Control Experiment

Given the poor performance in we wanted to test whether children's failure could be due to the way we designed the task. Indeed, since our results presented some contrasts with previous studies showing children were successful in using maps, it is possible to presume that our task was, in general, harder for children. Therefore, we tested children in a control task with a geometric cue that had already been shown by previous studies to be successful to use (Izard et al. 2014 Whinkler-Rhoad et al. 2013). In order to investigate the capacity of navigating and reading maps using angles, children aged from 30 to 42 months old were tested with fragmented arrays arranged in order to isolate the angle property in a map task.

10. Results

One sample t-tests were used to compare the children's proportion of correct choices to the chance level (0.5). They revealed that children didn't perform significantly above the level of chance ($t(15)=1.69$; $p=0.11$). In order to further explore the results, children were broken down into two age groups: 30 to 35 months and 36 to 42 months. One sample-t-tests were used to compare children's performance against the level of chance for any age group. The results showed that children didn't perform significantly above the level of chance in the younger age group ($t(6)=0$; $p=1$), but they performed significantly above the level of chance in the older age group ($t(8)=2.40$; $p=0.043$).

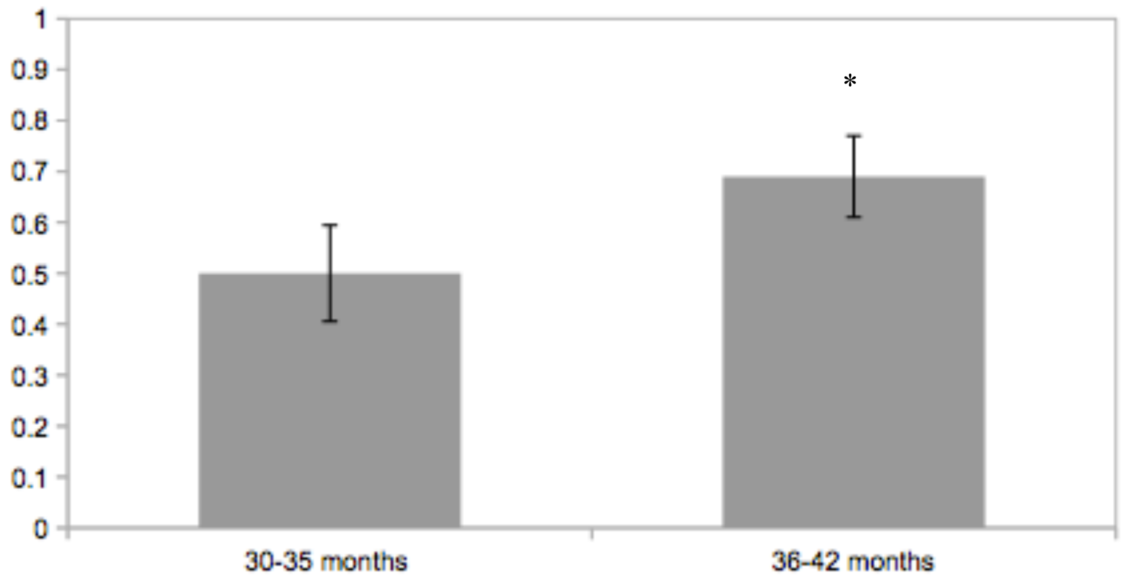


Figure 24. Proportion of correct choices averaged across subjects in the two age groups: 30 to 35 months and 36 to 42 months. *=p<0.05, **=p<0.01, ***=p<0.001.

11. Discussion

In this study we set out to gain insight into the role of the Euclidean geometric components of distance and length in children's ability to represent space for navigation. While children aged 30 to 42 months used distance to reorient in space, they failed at using length. However, children failed in using both distance and length in a map-placement task and succeeded in using angle from 36 months old.

Despite some limitations of our study due to the relatively small size of the sample that did not allow a full, in-depth data analysis, we can still try to draw initial, but, nonetheless, important conclusions from our results. First of all, we noticed that in the reorientation task children performed significantly above chance in the distance condition and not significantly above chance in the length condition. Moreover, there was a significant difference in the performance in the distance and length condition.

The first finding of our study is thus that children can use distance in reorientation from a very early age. This finding confirms previous studies showing that children can orient in fragmented arrays where distance and directions are the only cues present in the navigable space (Lee et al. 2012). Not only was this finding confirmed, but also generalized. Indeed, through our study we showed not only that children are able to use distance in enclosed spaces made up of four borders (Lee et al. 2012), but also in navigable spaces made up of two opposite walls.

Moreover, we showed the property of distance alone is sufficient to determine children's reorientation behavior: while previous studies showed children to be able to use distance in combination with sense, presenting children with four borders arrays (Lee et al. 2012; Yousif & Lourenco 2017), our two borders-array eliminated directional (or sense) information and exclusively provided information about distance from two opposite borders (both with respect to the center/subject and with respect to the surrounding walls).

These results, showing children's success in the reorientation task with borders placed at different distances, are in line with electrophysiological studies in animals, showing that place cells have sensitivity to distances and directions from extended borders (O'Keefe & Burgess 1996) and to computational models of the place cells' firing. In particular, a model (BVC) established that place cells' firing is activated by barrier-like surfaces placed at a particular distance and direction from the subject (Hartley, Burgess, Lever, Cacucci, & O'Keefe, 2000). Recent studies have discovered that cells that fit the BVC model (so called boundary-vector cells), provide input to place cells regarding the surrounding surface layout (Lever et al. 2009). Furthermore, although place cell firing is sensitive to extended surfaces, it is not sensitive to discrete objects or landmarks placed in the middle of the testing environment (Cressant, Muller, & Poucet 1997). If sensitivity to distances from the borders underlie place cells' activation in animals, our study might suggest that similar mechanisms used to compute locations in space are active in children. Further behavioral and neuro-imaging studies in children could help investigating this issue.

To sum up, this study supports the idea that a specific geometric spatial encoding system develops from an early age. Moreover, we add to the large body of evidence that encoding distances in the large-scale layout is an essential component of spatial mapping in navigation.

Furthermore, our study essentially contributes to the existing debate by helping to clarify which geometric properties children used in order to solve the reorientation task in geometric chambers. Indeed, in previous studies, researchers attempted to give an account of the role of geometric information in the success of children and animals in reorientation tasks with geometric arrays (Lourenco et al. 2009; Sovrano et al. 2002; Sovrano & Vallortigara 2006). They hypothesized children and animals to be able to use a combination of length and sense information to distinguish the two geometric equivalent corners in rectangular environments. And, according to them, a corner in a rectangular enclosure might be identified by its left or right position with respect to shorter or longer walls. Thus, children and animals would have been able to solve the task, for example, by searching in the corner that is on the left of the shorter wall. Our results are in contrast with this account, since we showed that children are able to rely on distance information alone to solve the reorientation task, and importantly, they cannot use length information. The accuracy level of the reorientation task by distance ranged between 70% and 80% and were not different from past studies on the use of geometric information in reorientation tasks (Learmonth et al. 2001, Lee et al. 2008; 2011), therefore it is possible to argue that distance alone (not in combination with either length or other geometric properties) was sufficient for children to solve the reorientation task.

It might be argued that children succeeded in the reorientation task by using surfaces as beacons. This idea would undermine our conclusion that children use the geometric property of distance to reorient by assuming that children are attracted by some specific features of the surfaces themselves rather than computing distances from the borders. Such a theory is to be disregarded based on the fact that children succeeded in the reorientation task in the distance condition with surfaces that were visually equivalent and not at all distinguishable on the basis of shape, length or color, while they failed in the length condition where surfaces could be clearly visually distinguished on the basis of length. Additionally, previous studies (Lee, Shusterman & Spelke 2006) have shown children can use objects as direct beacons only when they are distinguishable on the basis of shape and color. With the same argument we can also exclude accounts of children's reorientation capacity based on view image matching, a theory by which children find the correct position by matching their retinal image stored before the disorientation procedure to the visual environment they see after the disorientation procedure (Sturzl et al. 2008). Indeed, based on this theory, children would have been able to succeed in the length but not in the distance condition. On the other hand, our study confirms that the disorientation paradigm activates a navigation strategy other than beacon guidance and image matching that is based on computing distances from surfaces present in the navigating environment. It also confirms the human brain to be endowed, from very early in development, a navigation system that is based on the computation of distances and directions, and not length.

Finally, it is worth mentioning that in our study surfaces had both a different distance from the center (or from the subject placed at the center of the navigating environment) and a different distance from the borders of the experimental room (with a relevant ratio of 1:3). It is thus not possible to infer whether children reoriented by the difference in distance from the center or by the difference in distance of the surface from the borders. It is possible that children relied on a combination of the two, but future studies are needed in order to clarify which distance properties children tend to use for solving the reorientation task.

How did children perform in the map task? Children's performance in the map task was not significantly above the level of chance both for the distance and the length condition. However, children performed above the level of chance in the control task (starting from 36 months old) where they were presented with angles of different amplitudes.

The second finding of our study is therefore that children cannot use distance and length information in map tasks from the age of 30 to the age of 42 months. These results are not to be considered particularly striking given the fact that map tasks are somewhat difficult, because they require not only an ability to detect the properties of geometric images, an ability that emerges in humans from a very early age (Schwartz & Day 1979; Slater et al. 1991), but also an ability to match them with the corresponding elements in the large-scale 3D environment. Moreover, it is worth noticing that our results are not in contrast with previous findings that show children can use distance and length properties in map-tasks (Shusterman et al. 2008; Spelke et al. 2011; Dillon et al. 2013). This is because in these studies children were tested in an older age range and, as we mentioned above, they presented children with arrays in which these properties were mixed, making it difficult to understand which one they relied on to solve the map task.

Diversely, throughout our control task, we showed that children can compare angles in 3D and 2D environments and read them on maps from the age of 36 without instructions or corrective feedback. These results are in line with Izard et al. 2014 who showed that children are able to use fragmented angles from four years of age. Our results generalized this finding to children as young as three years of age. They confirm that at three years children can grasp the correspondence between a geometrical environment and its symbolic representation and can detect angle differences on a large-scale space as well as on a visual representation of it when not disoriented.

Why did children fail at using distance and length information and succeed at using angle?

Our results might be somewhat unexpected with respect to previous studies, in particular regarding children's inability to use length. While reorientation results, showing the use of distance but not length were somewhat expected based on previous findings (Lee et al. 2012), children's inability to use length in map tasks was surprising, given that children are proficient at using length in visual form analysis (Spelke et al. 2010). A possible reason for this failure is that the difference in length is not easy to grasp, because it requires children to perform a relative rather than an absolute comparison. Indeed, all distances and lengths are much shorter in the environment than in the map. Thus, children have to comprehend not the absolute difference but the difference in ratio between the lengths in the map and in the 3D environment. This might be challenging, because it requires a great degree of flexibility and abstraction, allowing a comparison of elements belonging to environments that are represented at different scales. The same argument can be applied to the use of distance in map-tasks, given the fact that in our experiment children didn't succeed at using distance in the map-placement task. However, it does not apply to angle, because the size of the angle has the same value on the map and in the environment (namely, a 60° angle in the map has the same dimension as a 60° corner in the large-scale space). It is possible that this factor makes angle the easiest aspect to be grasped from maps and exploited in the navigable environment. Future studies investigating the developmental pattern in the use of length and distance in map tasks can help establish whether children acquire the capacity of abstraction required for processing maps later in development.

Nonetheless, it is worth noticing that the discrepancy in the use of length in 2D visual form analysis and maps might indicate these two competences follow different developmental trajectories and are mediated by different systems (or by only partially overlapping systems, since the capacity of reading maps still requires, to some degree, the analysis of the 2D shape). It is possible to presume that children's capacity of using geometric cues in maps such as distance and length arises later because matching the 3D environment and the 2D shape requires an even higher degree of abstraction with respect to the simpler 2D shape analysis.

Our overall results might be considered to be in contrast with Winkler-Rhoades et al. (2013). In this study, slightly younger children (aged 28 to 32 months) than in other studies were tested in a map task with either linear or triangular arrays (both constituted by single objects and by continuous surfaces). Although they couldn't use distance information provided by the linear array made up of a row of three single objects, they were shown to be able to use distance information, together with angle information, in the triangular array made up of continuous surfaces. Apart from the difference in the arrays used, this study presented some similarities with our study. Namely, the maps were presented to the children irrespectively of the differences between the map and array in orientation, size, dimensionality and perspective. Furthermore, as in our study, no prior explicit training nor corrective feedback was given to the children. What then, could explain the discrepancy? An important difference might lie in the fact that in the Whinkler-Rhoades study, children were provided with more detailed instructions. Before starting the experiment, they were given four memory-checks and two warm-up trials. During memory-checks, the child was asked to repeatedly point to a target location, which was previously shown on the map by the experimenter, with the map positioned at four possible orientations. This procedure was aimed at ensuring children could attend to the information present in the map and could correctly memorize one location on it. During warm-up trials, the child was presented with a map that had two colored boxes and they were asked to place the toy into one of them. The preparatory trials we described were not aimed at testing spatial competence, but at ensuring children could understand the symbolic value of the map and establish a link between the large-scale and the small-scale environments. These kinds of instructions might nonetheless have enhanced children's performance, given that previous studies (Huttenloacher et al. 2008, De Loache 1999) showed that children might benefit from a preparatory training before the task in order to understand the symbolic value of the small-scale picture. Future map studies, involving training sessions, are needed in order to better investigate this issue.

However, despite some discrepancies with previous map-studies that show children being successful, it is not possible to attribute children's failure in our map study to the task difficulty. Namely, it is possible to argue the observed performance was not significantly above the level of chance both in the distance and in the length condition due to the fact that our design was in general too hard for children. This hypothesis is to be disregarded, since we showed that children succeeded on a similar task and with similar experimental procedures, with a different spatial cue, such as the angle.

It is worth mentioning that this study confirms that different spatial processes underlie the capacity to move and orient in a 3D environment and to read a map (Spelke et al., 2010). Young children can adeptly use distance information in reorientation, but they cannot encode it in a map task. Length information, on the other hand, cannot be used in navigation or in map-reading. Angle information can be used in a map reading task from 36 months old. Therefore, our study shows that the same geometric properties are used differently in different spatial tasks (namely navigation and map-tasks). These results are relevant and informative as long as they provide an insight into the distinct cognitive processes underlying spatial cognition and their development. Moreover, at a more general level, they inform about the development of geometric competences in children. Finally, they support the existence of (at least) two different cognitive mechanisms underlying geometric abilities with different developmental trajectories and probably different brain correlations.

Lastly, our study essentially contributes to the debate in the spatial navigation field by showing that the exclusive property children can use in order to solve the reorientation task is distance, and not length as was previously hypothesized (Yousif and Lourenco 2017). We were able to show this by adopting an array made up of two border surfaces that definitely prevented any chance of amodal completion by the children. Moreover, we also clarified which properties can be used in map tasks, since previous studies claimed that children can use maps but they mixed the three properties of distance, angle and length making it difficult to understand which one children relied on in order to solve the map task. In our study, we showed that young children cannot use distance and length in map tasks and the use of geometric cues in map tasks is limited to the angle. In general, our study confirms there is a dissociation in the use of distance and length in reorientation and map-tasks and that map-use and reorientation follow distinct developmental patterns and provided an important insight into the development of geometric competences in children.

To conclude, is important to stress that our study has important limitations due to the relatively small size of the samples in every age group, which prevented us track relevant developmental changes, both in the reorientation and in the map task. Increasing the sample size is particularly important in order to make the tasks comparable across the two age groups (30 to 35 months and 36 to 42 months). In particular, from a power analysis (power 0.8) we estimated that the sample size should be increased up to 16 subjects for each age group (30 to 35 months and 36 to 42 months) both in the reorientation and map experiments.

References

For this third Chapter I want to thank Anna Gui, for the helpful and inspiring conversations we had about the interpretations and remarks on the results of the present experiment.

Cheng, K. (1986). A purely geometric module in the rat's spatial representation. *Cognition*, *23*(2), 149-178.

Cressant, A., Muller, R. U., & Poucet, B. (1997). Failure of centrally placed objects to control the firing fields of hippocampal place cells. *Journal of Neuroscience*, *17*(7), 2531-2542.

Dehaene, S., Izard, V., Pica, P., & Spelke, E. (2006). Core knowledge of geometry in an Amazonian indigene group. *Science*, *311*(5759), 381-384.

DeLoache, J. S., de Mendoza, O. A. P., & Anderson, K. N. (1999). Multiple factors in early symbol use: Instructions, similarity, and age in understanding a symbol-referent relation. *Cognitive development*, *14*(2), 299-312.

Dillon M. R., Huang Y., Spelke E.S. (2013). Core foundations of abstract geometry, PNAS, 1-5.

Gui A. (2015). Young children’s use of geometry in spatial cognition. Master thesis in Cognitive Neuroscience.

Hartley, T., Burgess, N., Lever, C., Cacucci, F., & O'Keefe, J. (2000). Modeling place fields in terms of the cortical inputs to the hippocampus. *Hippocampus*, *10*(4), 369-379.

Hermer, L., & Spelke, E. S. (1994). A geometric process for spatial reorientation in young children. *Nature*, *370*(6484), 57.

Hermer, L., & Spelke, E. (1996). Modularity and development: The case of spatial reorientation. *Cognition*, *61*(3), 195-232.

Hupbach, A., & Nadel, L. (2005). Reorientation in a rhombic environment: No evidence for an encapsulated geometric module. *Cognitive Development*, *20*(2), 279-302.

Huttenlocher, J., Newcombe, N., & Vasilyeva, M. (1999). Spatial scaling in young children. *Psychological Science*, *10*(5), 393-398.

Huttenlocher J., Vasilyeva M., Newcombe N., Duffy S. (2008). Developing symbolic capacity one step at a time, *Cognition*, 106, 1-12.

Learmonth, A. E., Newcombe, N. S., & Huttenlocher, J. (2001). Toddlers' use of metric information and landmarks to reorient. *Journal of experimental child psychology*, *80*(3), 225-244.

Lee, S. A., Sovrano, V. A., & Spelke, E. S. (2012). Navigation as a source of geometric knowledge: Young children's use of length, angle, distance, and direction in a reorientation task. *Cognition*, *123*(1), 144-161.

Lee, S. A., Shusterman, A., & Spelke, E. S. (2006). Reorientation and landmark-guided search by young children: Evidence for two systems. *Psychological Science*, *17*(7), 577-582.

Lee, S. A., & Spelke, E. S. (2008). Children's use of geometry for reorientation. *Developmental science*, *11*(5), 743-749.

Lee, S. A., & Spelke, E. S. (2011). Young children reorient by computing layout geometry, not by matching images of the environment. *Psychonomic bulletin & review*, *18*(1), 192-198.

Lee, S. A., Vallortigara, G., Flore, M., Spelke, E. S., & Sovrano, V. A. (2013). Navigation by environmental geometry: the use of zebrafish as a model. *Journal of Experimental Biology*, *216*(19), 3693-3699.

Lever, C., Burton, S., Jeewajee, A., O'Keefe, J., & Burgess, N. (2009). Boundary vector cells in the subiculum of the hippocampal formation. *Journal of Neuroscience*, *29*(31), 9771-9777.

Lourenco, S. F., & Huttenlocher, J. (2006). How do young children determine location? Evidence from disorientation tasks. *Cognition*, *100*(3), 511-529.

Lourenco, S. F., Addy, D., & Huttenlocher, J. (2009). Location representation in enclosed spaces: What types of information afford young children an advantage?. *Journal of Experimental Child Psychology*, *104*(3), 313-325.

Newcombe, N. S., Ratliff, K. R., Shallcross, W. L., & Twyman, A. D. (2010). Young children's use of features to reorient is more than just associative: Further evidence against a modular view of spatial processing. *Developmental science*, *13*(1), 213-220.

O'Keefe, J., & Burgess, N. (1996). Geometric determinants of the place fields of hippocampal neurons. *Nature*, *381*(6581), 425.

Schwartz M., Day R.H. (1979). Visual shape perception in early infancy, Monographs of the Society for Research in Child Development, 44(7):1-63.

Shusterman A., Lee S.A., Spelke E.S. (2008). Young children's spontaneous use of geometry in maps, *Developmental Science*, 11(2): 1-9.

Slater A., Mattock A., Brown E., Bremner J.G. (1991). Form Perception at Birth: Cohen and Younger (1984) Revisited, Journal of experimental child psychology, 51, 395-406.

Sovrano, V. A., Bisazza, A., & Vallortigara, G. (2002). Modularity and spatial reorientation in a simple mind: Encoding of geometric and nongeometric properties of a spatial environment by fish. *Cognition*, *85*(2), B51-B59.

Sovrano, V. A., & Vallortigara, G. (2006). Dissecting the geometric module: A sense linkage for metric and landmark information in animals' spatial reorientation. *Psychological Science*, *17*(7), 616-621.

Spelke E.S., Gilmore C.K., McCarthy S., (2011), Kindergarten children's sensitivity to geometry in maps, *Developmental Science,* 14:4, 809–821.

Spelke, E., Lee, S. A., & Izard, V. (2010). Beyond core knowledge: Natural geometry. *Cognitive science*, *34*(5), 863-884.

Stürzl, W., Cheung, A., Cheng, K., & Zeil, J. (2008). The information content of panoramic images I: The rotational errors and the similarity of views in rectangular experimental arenas. *Journal of Experimental Psychology: Animal Behavior Processes*, *34*(1), 1.

Vasilyeva, M., & Bowers, E. (2006). Children's use of geometric information in mapping tasks. *Journal of Experimental Child Psychology*, *95*(4), 255-277.

Winkler-Rhoades N., Carey S.C., Spelke E.S. (2013). Two-year-old children interpret abstract, purely geometric maps, *Developmental Science*, 16:3, 365- 376.

Wystrach, A., & Beugnon, G. (2009). Ants learn geometry and features. *Current Biology*, *19*(1), 61-66.

Yousif, S. R., & Lourenco, S. F. (2017). Are all geometric cues created equal? Children's use of distance and length for reorientation. *Cognitive Development*, *43*, 159-169.

General Discussion

Navigation by boundary geometry has been widely studied and documented in animals and humans (Cheng & Newcombe 2005; 2006 for review), but the factors that define a surface as a boundary that can be used in navigation are yet to be clarified. In our first study, we set out to understand whether children are sensitive to boundaries that are conceived as visual or physical obstacles. To this aim, we tested a group of children from 2 to 7 years of age in a reorientation task with a rectangular array of either transparent or opaque surfaces. We found out that while children are able to use opaque surfaces at all ages, they become able to use transparent surfaces at the age of five. Therefore, we concluded that the visual component of boundaries is crucial in early ages. What explains the failure of the 2-4-year-olds in using transparent boundaries and the subsequent change around the age of five? Firstly, as shown by the control tests, it is unlikely that young children simply failed to perceive the transparent boundaries or failed to understand that they are solid, physical barriers. A possible explanation is that it takes time for them to integrate conflicting information represented, on the one end, by the visual input, which indicates an absence of visually occlusive boundaries and the physical input, on the other hand, which indicates the presence of a consistent environmental surface structure. Indeed, it is possible to presume that younger children's brain function may not be mature enough to process the input that indicates the presence of a physical boundary (provided by the transparent surfaces) independently from the visual stimulus, or to inhibit the visual input indicating an absence of boundaries.

In our second study, we set out to investigate the role of boundaries made up of objects in children's navigation. Previous studies had shown that children failed in orienting by geometric configurations of three or four objects. It might be argued that children failed in using these structures because they were not sufficiently dense to prevent movement or because they were not sufficiently dense to visually underline the geometric structure. In our first experiment, we tested children from 4 to 9 years of age with a rectangular configuration of 20 closely aligned objects. This configuration was sufficiently dense to prevent movement and to underline the geometric structure. We found out that children are not able to use these configurations of objects until the seventh year of age. Thus, we argued that children's inability to use a geometric objects' configuration is tied to its specificity of being discontinuous. But what distinguishes a boundary from an object? In our second experiment we tried to investigate which is the length of the boundaries at which children succeeded in the reorientation task. To this aim, we tested children with continuous boundaries of either 50 cm or 100 cm. We showed that children can use these structures to reorient at all ages.

Why did children fail in using configurations of separate objects to navigate? On one hand, a possible account for such a failure lies in the presumed separation of cognitive processes and parts of the brain supporting the use of boundaries for navigation, and the use of landmarks and features on the other. Some studies have shown that the capacity of using landmarks arises late in children's development and protracts until adolescence. Thus, the results might be explained on the basis of the difficulty for children to process information coming from objects or to integrate information coming from the layout of the rectangular structure and from the discrete objects. On the other side, our study confirms that children are able to use continuous, extended walls at all ages. This is the first study in which children were tested with surfaces as short as 50 cm and were shown to succeed.

Our third study concerned the use of distance and length (and angle) in reorientation and map tasks. Previous studies have investigated the use of distance and length in reorientation and map tasks, but no study had carefully isolated these properties and tested their use both in a reorientation task and map tasks with the same group of children of 2.5 to 3.5 years of age in the same experimental environment in order to make the two tasks comparable. In this study we first showed that 30 to 42 month-old children are able to use distance (but not length) in the reorientation task. These results are in line with previous behavioral studies with children (Lee et al. 2012), showing they are able to rely on distance to reorient and with electrophysiological studies showing that place cells compute distances and directions from the boundaries of the testing environments. Secondly, in our third study, we showed that children are not able to use distance or length in map-tasks, while they are able to use angle from 36 months. Why did children fail in using distance and length on a map? A possible reason for this failure is that all distances and lengths are much shorter in the map than in the environment. Thus, children have to catch a relative, rather than an absolute difference between a couple of elements in two different environments (the navigating environment and the small-scale map). This ability might be particularly challenging and requires a great degree of cognitive flexibility that children might acquire later in development. The same argument doesn't apply to the angle cue, since the difference in amplitude of the two angles is absolute rather than relative as it is preserved in the 2D and 3D environments. Namely the angles have the same amplitude in both environments, this might be the reason why the correspondence of angles in the 3D environment and in the map is easier for children to grasp.

Conclusions

Converging evidence from various fields of cognitive research, from psychology to neurobiology, focused on the existence of a cognitive system that is able to process spatial boundaries. Our three studies make an important contribution to the understanding of which perceptual and physical factors define boundaries and gave an important insight into the development of children's boundaries' representation.

Our first study suggests that the visual factor is crucial for children below the age of five, despite the fact that even 2-year-olds demonstrate a basic understanding of the solidity and functional relevance of transparent surfaces as obstacles to movement. In future work, it might be interesting to further investigate how the physical material that constitute boundaries plays a role in their use in navigation. For example, it might be interesting to test how children behave with respect to boundaries that are devoid of their physical occlusiveness, but keep their visual quality. Soft surfaces that are able to be manipulated, but keep their visual robustness, would be an ideal mean to test children's use of boundaries that are visually but not physically occlusive.

Our second study suggests that the boundaries' continuity is crucial for children below the age of six, both for their use in the reorientation task and the correct identification of their drawing, as the results of the post-test might suggest. The underlying cause behind children's failure to use boundaries made up of discrete objects might be that objects and boundaries constitute qualitatively different elements of the navigable space and are presumably processed by distinct mechanisms in the brain. Future studies investigating neural underpinnings of children's use of boundaries and objects in navigation might help clarify this issue. Moreover, as we saw children succeed with both 100 cm long and 50 cm long boundaries, therefore it might be interesting to uncover the length at which a boundary might be distinguished from an object by testing children with even shorter boundaries.

Our third study showed that children are able to use distance between borders but not length from very early on in reorientation tasks. This result might be rooted in the evidence showing that place cells preferably respond to distance and direction from the borders, even in newborn rats. Furthermore, this study, by showing that children are unable to use distance and length in map tasks, confirms a dissociation in the use of these geometric elements in navigation and 2D shape analysis. Because this study took a small cross section of 2-3-year-olds, it would be interesting to widen the age range in order to investigate how and when the use of geometric cues changes over development, both in navigation and in maps tasks.

After analyzing separately the outcomes of our three studies and suggesting possible ways to keep on with each single study we can move to more general observations. In particular, in this final part of our work, by highlighting common conclusions across the three studies we aim at discussing how our findings contributed to the debate in the spatial navigation field, which fundamental issues they either solved or raised in light of existing hypothesis, and which new experimental questions they suggested.

Our studies in general, besides being useful to specify the aspects and properties of the stimuli that are preferentially used in navigation provided a deeper insight into the mechanisms regulating spatial navigation in children and, more generally, in humans. In line with other studies (Negen et al. 2018) both study 1 and study 2 emphasize the role of visual appearance of boundaries over their role of being obstacles for movement. Indeed, even if the boundaries constitute solid obstacles for movement, they are not used by young children in order to solve the spatial navigation task. Both the transparent arena and the discontinuous boundary made up of discrete objects seem to lack the essential visual features such as opacity and continuity that seem to constitute the key aspects of a boundary that are used in navigation by young children. The visual opacity and continuity of boundaries are crucial elements for identifying boundaries and use in reorientation by children.

Why is the visual appearance of boundaries so crucial for children? It is possible that, early in development, especially for animals that highly rely on vision, the visual input is the only one guiding navigation. Therefore, although our hippocampal spatial representations are not solely fixed to the visual modality, early in development, we may have a more fragile sense of spatial structure that is easily perturbed by the absence of boundaries clearly constituting visual barriers.

The predominance of the visual modality in guiding navigation in early stage of development might be specific of humans, given that the evidence shows that place cells in animals are active in rats also in the dark and in blind-born rats (Quirk, Müller & Kubie, 1990; Save, Cressant, Thinus-Blanc & Poucet, 1998) and therefore it is possible to presume that the visual one is not the primary input upon which rats based their navigation and sense of orientation.

The importance of the visual modality that emerges throughout our studies might be also linked with the involvement, that is specific of humans, of the brain areas mediating the analysis of visual scenes (see Chapter 1, Introduction).

Our studies thus confirms that besides a series of common, presumably phylogenetically preserved mechanisms in spatial navigation, i.e. sensitivity towards boundary-geometry, there are species-specific differences also among mammals (as for the use of boundaries and features, see the General Introduction). Rodents and humans might rely on input from different modalities in order to process and recognize locations in space. These modalities might be related to the ecological niche, given that vision is the primary modality in humans.

Nonetheless the hypothesis of a predominance of the visual aspect of boundaries early in development needs to find a confirmation in future experiments testing children not only with boundaries that preserve their visual aspect but lack their solidity as obstacles for movement, i.e. manipulable surfaces, but also, as long as it possible to build a safe experimental environment e.g in virtual environments, with boundaries that constitute purely obstacles to movement, such as cliff-like edges, as it was done for animals. It would also be interesting to evaluate the contribute of other sensory modalities in navigation in children, for example to evaluate the role of the physical or tactile input in the use of boundaries and test children and adults in the dark or test congenitally blind children, as well as to study the contribute of the vestibular and proprioceptive information. Finally, it would be interesting to clarify the role of visual scene selective areas in navigation both in children and adults, also because it seems they respond differently to different aspects of the boundaries (their visual appearance or their being obstacles to movement, Ferrara & Park, 2016). Studying the development of these areas could provide a further insight into how the processing of different aspects of boundaries develops in children.

On the other hand, in order to better understand children's failure in the use of boundaries made up of closely aligned objects, it would be definitely important to establish the age benchmarks characterizing the developmental trajectory of children use of objects in navigation and in particular in the reorientation task. Indeed, while the use of boundaries was widely studied, the developmental trajectory in the use of objects as either direct or indirect landmarks received less attention. Finding similar age-benchmarks, as in our study, could help us confirming the failure we observed until the age of seven, to be due to children's late development of the ability to use of objects in navigation.

If study 1 and 2 results suggested somewhat a distance between humans and other species in spatial navigation abilities, study 3 confirmed the existence of common traits among different species. Young children use of distance can be linked to a wealth of neurophysiological studies showing place cells sensitivity to distance from the borders in rodents. Are children sensitive to distance because they share a common neural substrate mediating spatial navigation with other animals e.g. place cells?

Future research, in particular neuro-imaging studies and electrophysiological studies in patients, has to define this point.

From a developmental point of view, our three studies are important because they highlight there are important developmental changes occur in spatial navigation. Children sensitivity to different materials and visual aspects of boundaries are submitted to fundamental changes over development, and not all geometric cues are equally used by young children in navigation. In general, our studies argue for an abstraction capacity that is acquired later in development affecting spatial representations. Study 1 showed that children acquire the capacity of abstracting from the visual input at the age of five. Study 2 showed that children acquire the capacity of extrapolating (by abstraction) the geometric shape of the array by integrating objects' and boundaries' information at the age of seven. Study 3 tells us that young children can only process distance in navigation and angle in map-reading tasks and leaves open the possibility that they acquire the capacity of integrating more complex geometric properties and implement more sophisticated 2D and 3D shape analysis later in development. Future studies using multiple different spatial cues, and comparing different tasks involving the use of geometry at different degrees of abstraction, are needed in order to understand whether an abstraction capacity plays a role into the acquisition of the capacity to solve our tasks.

Nonetheless the initial conclusions we were able to draw so far from our three studies, gave an essential input to the developmental debate because they inform which material, physical and visual properties of boundaries children are most sensitive to and at which stage of development and they can help understanding how to design and build safe environments for children.

Finally, to conclude, several studies have shown the importance of geometry for navigation from a very early age. Some researchers suggested that the use of geometry in navigation, as well as in small-scale environments, might play an important role in children's building and acquisition of concepts of Euclidean plane geometry (Spelke, Lee & Izard 2010) and proposed that training children in combining the geometry of large-scale and small-scale environments (like maps, pictures and models) may positively affect their learning and understanding of abstract geometry (Spelke 2011). Our studies showed that the material and perceptual characteristics of the structures constituting geometric shapes affect the way geometry is used and perceived in navigation. Therefore, our studies contribute to this line of research by indicating which materials, objects and geometric shapes could eventually maximize children's process of learning geometry.

References

Barry, C., Lever, C., Hayman, R., Hartley, T., Burton, S., O'Keefe, J., ... & Burgess, N. (2006). The boundary vector cell model of place cell firing and spatial memory. *Reviews in the Neurosciences*, *17*(1-2), 71-98.

Biegler, R. (2000). Possible uses of path integration in animal navigation. *Learning & Behavior*, *28*(3), 257-277.

Bird, C. M., Capponi, C., King, J. A., Doeller, C. F., & Burgess, N. (2010). Establishing the boundaries: the hippocampal contribution to imagining scenes. *Journal of Neuroscience*, *30*(35), 11688-11695.

Bullens, J., Nardini, M., Doeller, C. F., Braddick, O., Postma, A., & Burgess, N. (2010). The role of landmarks and boundaries in the development of spatial memory. *Developmental Science*, *13*(1), 170-180.

Burgess N. (2006). Spatial memory: How egocentric and allocentric combine. Trends in Cognitive Sciences.; 10:551–557.

Burgess, N. (2008). Spatial cognition and the brain. *Annals of the New York Academy of Sciences*, *1124*(1), 77-97.

Burgess N. (2014). The 2014 Nobel Prize in Physiology or Medicine: A Spatial Model for Cognitive Neuroscience. Neuron, 84(6):1120–1125.

Cheng, K. (1986). A purely geometric module in the rat's spatial representation. *Cognition*, *23*(2), 149-178.

Cheng, K. (2008). Whither geometry? Troubles of the geometric module. *Trends in cognitive sciences*, *12*(9), 355-361.

Cheng, K., & Gallistel, C. R. (1984). Testing the geometric power of an animal's spatial representation. In H. L. Roitblatt, T. G. Bever & H. S. Terrace (Eds.), Animal cognition (pp. 409–423). Hillsdale, NJ: Erlbaum.

Cheng, K., Huttenlocher, J., & Newcombe, N. S. (2013). 25 years of research on the use of geometry in spatial reorientation: a current theoretical perspective. *Psychonomic bulletin & review*, *20*(6), 1033-1054.

Cheng, K., & Newcombe, N. S. (2005). Is there a geometric module for spatial orientation? Squaring theory and evidence. *Psychonomic bulletin & review*, *12*(1), 1-23.

Cheng, K., & Newcombe, N. S. (2006). Geometry, features, and orientation in vertebrate animals: a pictorial review. *Animal spatial cognition: comparative, neural, and computational approaches. http://www. pigeon. psy. tufts. edu/asc/cheng*.

Chiandetti, C., & Vallortigara, G. (2008). Spatial reorientation in large and small enclosures: comparative and developmental perspectives. *Cognitive processing*, *9*(4), 229-238.

Collett, T. S., & Collett, M. (2002). Memory use in insect visual navigation. *Nature Reviews Neuroscience*, *3*(7), 542-552.

Collett, T. S., & Graham, P. (2004). Animal navigation: path integration, visual landmarks and cognitive maps. *Current Biology*, *14*(12), R475-R477.

Cressant, A., Muller, R. U., & Poucet, B. (1997). Failure of centrally placed objects to control the firing fields of hippocampal place cells. *Journal of Neuroscience*, *17*(7), 2531-2542.

Derdikman, D., & Moser, E. I. (2010). A manifold of spatial maps in the brain. *Trends in cognitive sciences*, *14*(12), 561-569.

Doeller, C. F., & Burgess, N. (2008). Distinct error-correcting and incidental learning of location relative to landmarks and boundaries. *Proceedings of the National Academy of Sciences*, *105*(15), 5909-5914.

Doeller, C. F., King, J. A., & Burgess, N. (2008). Parallel striatal and hippocampal systems for landmarks and boundaries in spatial memory. *Proceedings of the National Academy of Sciences*, *105*(15), 5915-5920.

Eichenbaum, H., Dudchenko, P., Wood, E., Shapiro, M., & Tanila, H. (1999). The hippocampus, memory, and place cells: is it spatial memory or a memory of space?. *Neuron*, *23*(2), 209-226.

Ekstrom, A. D., Kahana, M. J., Caplan, J. B., & Fields, T. A. (2003). Cellular networks underlying human spatial navigation. *Nature*, *425*(6954), 184.

Etienne, A. S., & Jeffery, K. J. (2004). Path integration in mammals. *Hippocampus*, *14*(2), 180-192.

Etienne, A. S., Maurer, R., Berlie, J., Reverdin, B., Rowe, T., Georgakopoulos, J., & Séguinot, V. (1998). Navigation through vector addition. *Nature*, *396*(6707), 161-164.

Etienne, A. S., Maurer, R., & Séguinot, V. (1996). Path integration in mammals and its interaction with visual landmarks. *Journal of Experimental Biology*, *199*(1), 201-209.

Epstein, R. (2005). The cortical basis of visual scene processing. *Visual Cognition*, *12*(6), 954-978.

Epstein, R. A. (2008). Parahippocampal and retrosplenial contributions to human spatial navigation. *Trends in cognitive sciences*, *12*(10), 388-396.

Epstein, R., & Kanwisher, N. (1998). A cortical representation of the local visual environment. *Nature*, *392*(6676), 598.

Ferrara, K., & Landau, B. (2015). Geometric and featural systems, separable and combined: Evidence from reorientation in people with Williams syndrome. *Cognition*, *144*, 123-133.

Ferrara, K., & Park, S. (2016). Neural representation of scene boundaries. *Neuropsychologia*, *89*, 180-190.

Gallistel, C. R. (1990). *The organization of learning* (pp. 317-350). Cambridge, MA: MIT press.

Gallistel, C. R. (1998). Symbolic processes in the brain: The case of insect navigation. *An invitation to cognitive science*, *4*, 1-51.

Gee, A. P., Chekhlov, D., Calway, A., & Mayol-Cuevas, W. (2008). Discovering higher level structure in visual SLAM. *IEEE Transactions on Robotics*, *24*(5), 980-990.

Gould, J. L. (1986). The locale map of honey bees: do insects have cognitive maps? Science, 232, 861-863.

Gentner D. A study of early word meaning using artificial objects: What looks like a jiggy but acts like a zimbo? (1978). Papers and Reports on Child Language Development, 15, 1–6, Stanford University. In: Gardner J, editor. Readings in developmental psychology. 2nd ed. Boston: Little Brown. pp. 137–142.

Gianni E. (2015). Behavioral and neural correlates of reorientation by boundaries and features. Master thesis in Cognitive Neuroscience.

Gouteux, S., & Spelke, E. S. (2001). Children's use of geometry and landmarks to reorient in an open space. *Cognition*, *81*(2), 119-148.

Gouteux, S., Thinus-Blanc, C., & Vauclair, J. (2001). Rhesus monkeys use geometric and nongeometric information during a reorientation task. *Journal of Experimental Psychology: General*, *130*(3), 505.

Hartley, T., Burgess, N., Lever, C., Cacucci, F., & O'Keefe, J. (2000). Modeling place fields in terms of the cortical inputs to the hippocampus. *Hippocampus*, *10*(4), 369-379.

Hartley, T., Lever, C., Burgess, N., & O'Keefe, J. (2014). Space in the brain: how the hippocampal formation supports spatial cognition. *Phil. Trans. R. Soc. B*, *369*(1635), 20120510.

Hermer, L., & Spelke, E. S. (1994). A geometric process for spatial reorientation in young children. *Nature*, *370*(6484), 57.

Hermer, L., & Spelke, E. (1996). Modularity and development: The case of spatial reorientation. *Cognition*, *61*(3), 195-232.

Hermer-Vazquez, L. (1997). Cognitive flexibility as it emerges over evolution and human development: The case of spatial reorientation. *Unpublished doctoral dissertation, Cornell University*.

Hermer-Vazquez, L., Moffet, A., & Munkholm, P. (2001). Language, space, and tdevelopment of cognitive flexibility in humans: The case of two spatial memory tasks. *Cognition*, *79*(3), 263-299.

Hupbach, A., & Nadel, L. (2005). Reorientation in a rhombic environment: No evidence for an encapsulated geometric module. *Cognitive Development*, *20*(2), 279-302.

Huttenlocher, J., & Lourenco, S. F. (2007). Coding location in enclosed spaces: is geometry the principle?. *Developmental science*, *10*(6), 741-746.

Huttenlocher, J., & Vasilyeva, M. (2003). How toddlers represent enclosed spaces. *Cognitive Science*, *27*(5), 749-766.

Huttenlocher J., Vasilyeva M., Newcombe N., Duffy S., (2008), Developing symbolic capacity one step at a time, *Cognition*, 106, 1-12.

Kelly, D. M., & Spetch, M. L. (2001). Pigeons encode relative geometry. *Journal of Experimental Psychology: Animal Behavior Processes*, *27*(4), 417.

Kelly, D. M., & Spetch, M. L. (2004). Reorientation in a two-dimensional environment: II. Do pigeons (Columba livia) encode the featural and geometric properties of a two-dimensional schematic of a room?. *Journal of Comparative Psychology*, *118*(4), 384.

Kelly, D. M., Spetch, M. L., & Heth, C. D. (1998). Pigeons'(Columba livia) encoding of geometric and featural properties of a spatial environment. *Journal of Comparative Psychology*, *112*(3), 259.

Killian, N. J., Jutras, M. J., & Buffalo, E. A. (2012). A map of visual space in the primate entorhinal cortex. *Nature*, *491*(7426), 761.

Kosslyn, S. M., Pick Jr, H. L., & Fariello, G. R. (1974). Cognitive maps in children and men. *Child development*, 707-716.

Julian, J. B., Ryan, J., Hamilton, R. H., & Epstein, R. A. (2016). The occipital place area is causally involved in representing environmental boundaries during navigation. *Current Biology*, *26*(8), 1104-1109.

Landau, B., & Lakusta, L. (2009). Spatial representation across species: Geometry, language, and maps. *Current opinion in neurobiology*, *19*(1), 12-19.

Landau B, Smith LB, Jones S. (1988). The importance of shape in early lexical learning. Cognitive Development. 3:299–321.

Learmonth, A. E., Nadel, L., & Newcombe, N. S. (2002). Children's use of landmarks: Implications for modularity theory. *Psychological Science*, *13*(4), 337-341.

Learmonth, A. E., Newcombe, N. S., & Huttenlocher, J. (2001). Toddlers' use of metric information and landmarks to reorient. *Journal of experimental child psychology*, *80*(3), 225-244.

Learmonth, A. E., Newcombe, N. S., Sheridan, N., & Jones, M. (2008). Why size counts: Children's spatial reorientation in large and small enclosures. *Developmental Science*, *11*(3), 414-426.

Lee, S. A., Sovrano, V. A., & Spelke, E. S. (2012). Navigation as a source of geometric knowledge: Young children's use of length, angle, distance, and direction in a reorientation task. *Cognition*, *123*(1), 144-161.

Lee, S. A., & Spelke, E. S. (2008). Children's use of geometry for reorientation. *Developmental science*, *11*(5), 743-749.

Lee, S. A., & Spelke, E. S. (2010a). A modular geometric mechanism for reorientation in children. *Cognitive psychology*, *61*(2), 152-176.

Lee, S. A., & Spelke, E. S. (2010b). Two systems of spatial representation underlying navigation. *Experimental Brain Research*, *206*(2), 179-188.

Lee, S. A., & Spelke, E. S. (2011). Young children reorient by computing layout geometry, not by matching images of the environment. *Psychonomic bulletin & review*, *18*(1), 192-198.

Lee, S. A., Vallortigara, G., Flore, M., Spelke, E. S., & Sovrano, V. A. (2013). Navigation by environmental geometry: the use of zebrafish as a model. *Journal of Experimental Biology*, *216*(19), 3693-3699.

Lever, C., Burton, S., Jeewajee, A., O'Keefe, J., & Burgess, N. (2009). Boundary vector cells in the subiculum of the hippocampal formation. *Journal of Neuroscience*, *29*(31), 9771-9777.

Lever, C., Wills, T., Cacucci, F., Burgess, N., & O'keefe, J. (2002). Long-term plasticity in hippocampal place-cell representation of environmental geometry. *Nature*, *416*(6876), 90-94.

Lew, A. R. (2011). Looking beyond the boundaries: time to put landmarks back on the cognitive map?. *Psychological bulletin*, *137*(3), 484.

Lew, A. R., Foster, K. A., Bremner, J. G., Slavin, S., & Green, M. (2005). Detection of geometric, but not topological, spatial transformations in 6-to 12-month-old infants in a visual exploration paradigm. *Developmental psychobiology*, *47*(1), 31-42.

Lourenco, S. F., Huttenlocher, J., & Vasilyeva, M. (2005). Toddlers' representations of space: The role of viewer perspective. *Psychological Science*, *16*(4), 255-259.

Lourenco, S. F., & Huttenlocher, J. (2006). How do young children determine location? Evidence from disorientation tasks. *Cognition*, *100*(3), 511-529.

Lourenco, S. F., & Huttenlocher, J. (2007). Using geometry to specify location: Implications for spatial coding in children and nonhuman animals. *Psychological Research*, *71*(3), 252-264.

Lourenco, S. F., Huttenlocher, J., & Fabian, L. (2005). Coding geometric information in infancy. In *Poster presented at the Biennial Meeting of the Cognitive Development Society (CDS), San Diego, CA*.

Margules, J., & Gallistel, C. R. (1988). Heading in the rat: Determination by environmental shape. *Learning & behavior*, *16*(4), 404-410.

Menzel, E. W. (1973). Chimpanzee spatial memory organization. Science 182, 943-5.

Mittelstaedt, M.L., & Mittelstaedt, H. (1980). Homing by path integration in a mammal. *Naturwissenschaften*, *67*(11), 566-567.

Moser, E. I., Kropff, E., & Moser, M. B. (2008). Place cells, grid cells, and the brain's spatial representation system. *Annual review of neuroscience*, *31*.

Mou, W., & Zhou, R. (2013). Defining a boundary in goal localization: Infinite number of points or extended surfaces. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *39*(4), 1115.

Müller, M., & Wehner, R. (1988). Path integration in desert ants, Cataglyphis fortis. *Proceedings of the National Academy of Sciences*, *85*(14), 5287-5290.

Müller, M., & Wehner, R. (1994). The hidden spiral: systematic search and path integration in desert ants, Cataglyphis fortis. *Journal of Comparative Physiology A: Neuroethology, Sensory, Neural, and Behavioral Physiology*, *175*(5), 525-5530.

Negen, J., Sandri, A., Lee, S. A., & Nardini, M. (2018). Boundaries in Spatial Cognition: How They Look is More Important than What They Do. *bioRxiv*, 391037.

Newcombe, N., & Liben, L. S. (1982). Barrier effects in the cognitive maps of children and adults. *Journal of Experimental Child Psychology*, *34*(1), 46-58.

Newcombe, N. S., & Ratliff, K. R. (2007). Explaining the development of spatial reorientation. *The emerging spatial mind*, 53-76.

Newcombe, N. S., Ratliff, K. R., Shallcross, W. L., & Twyman, A. D. (2010). Young children's use of features to reorient is more than just associative: Further evidence against a modular view of spatial processing. *Developmental science*, *13*(1), 213-220.

O'Keefe, J. O., & Burgess, N. (1996). Geometric determinants of the place fields of hippocampal neurons. *Nature*, *381*(6581), 425.

O'Keefe, J., & Burgess, N. (2005). Dual phase and rate coding in hippocampal place cells: theoretical significance and relationship to entorhinal grid cells. *Hippocampus*, *15*(7), 853-866.

O'Keefe, J., & Dostrovsky, J. (1971). The hippocampus as a spatial map. Preliminary evidence from unit activity in the freely-moving rat. *Brain research*, *34*(1), 171-175.

O'Keefe, J., & Nadel, L. (1978). *The hippocampus as a cognitive map*. Oxford: Clarendon Press.

Olson, I. R., & Newcombe, N. S. (2013). Binding together the elements of episodes: Relational memory and the developmental trajectory of the hippocampus. *The Wiley Handbook on the Development of Children's Memory, Volume I/II*, 285-308.

Park, S., Brady, T. F., Greene, M. R., & Oliva, A. (2011). Disentangling scene content from spatial boundary: complementary roles for t he parahippocampal place area and lateral occipital complex in representing real-world scenes. *Journal of Neuroscience*, *31*(4), 1333-1340.

Park, S., & Chun, M. M. (2009). Different roles of the parahippocampal place area (PPA) and retrosplenial cortex (RSC) in panoramic scene perception. *Neuroimage*, *47*(4), 1747-1756.

Pierroutsakos SL, DeLoache JS (2003). Infants' manual exploration of objects varying in realism. Infancy. 4:141–156.

Ratliff, K. R., & Newcombe, N. S. (2008). Reorienting when cues conflict: Evidence for an adaptive-combination view. *Psychological science*, *19*(12), 1301-1307.

Schwartz M., Day R.H., (1979). Visual shape perception in early infancy, Monographs of the Society for Research in Child Development, 44(7):1-63.

Sheynikhovich, D., Chavarriaga, R., Strösslin, T., Arleo, A., & Gerstner, W. (2009). Is there a geometric module for spatial orientation? Insights from a rodent navigation model. *Psychological review*, *116*(3), 540.

Shusterman A., Lee S.A., Spelke E.S., (2008). Young children's spontaneous use of geometry in maps, *Developmental Science*, 11(2): 1-9.

Silveira, G., Malis, E., & Rives, P. (2008). An efficient direct approach to visual SLAM. *IEEE transactions on robotics*, *24*(5), 969-979.

Smith LB. (2009). From fragments to geometric shape: Changes in visual object recognition between 18 and 24 months. Current Directions in Psychological Science. 18:290–294.

Solstad, T., Boccara, C. N., Kropff, E., Moser, M. B., & Moser, E. I. (2008). Representation of geometric borders in the entorhinal cortex. *Science*, *322*(5909), 1865-1868.

Sovrano, V. A., Bisazza, A., & Vallortigara, G. (2002). Modularity and spatial reorientation in a simple mind: Encoding of geometric and nongeometric properties of a spatial environment by fish. *Cognition*, *85*(2), B51-B59.

Sovrano, V. A., Bisazza, A., & Vallortigara, G. (2007). How fish do geometry in large and in small spaces. *Animal cognition*, *10*(1), 47-54.

Sovrano, V. A., & Vallortigara, G. (2006). Dissecting the geometric module: A sense linkage for metric and landmark information in animals' spatial reorientation. *Psychological Science*, *17*(7), 616-621.

Spelke, E., Lee, S. A., & Izard, V. (2010). Beyond core knowledge: Natural geometry. *Cognitive science*, *34*(5), 863-884.

Spelke, E. S. (2011). Natural number and natural geometry. In *Space, time and number in the brain* (pp. 287-317).

Stürzl, W., Cheung, A., Cheng, K., & Zeil, J. (2008). The information content of panoramic images I: The rotational errors and the similarity of views in rectangular experimental arenas. *Journal of Experimental Psychology: Animal Behavior Processes*, *34*(1), 1.

Sutton, J. E., Twyman, A. D., Joanisse, M. F., & Newcombe, N. S. (2012). Geometry three ways: An fMRI investigation of geometric information processing during reorientation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *38*(6), 1530.

Tolman, E. C. (1948). Cognitive maps in rats and men. *Psychological review*, *55*(4), 189.

Tommasi, L., Chiandetti, C., Pecchia, T., Sovrano, V. A., & Vallortigara, G. (2012). From natural geometry to spatial cognition. *Neuroscience & Biobehavioral Reviews*, *36*(2), 799-824.

Vallortigara, G., Zanforlin, M., & Pasti, G. (1990). Geometric modules in animals' spatial representations: a test with chicks (Gallus gallus domesticus). *Journal of Comparative Psychology*, *104*(3), 248.

Vallortigara, G. (2009). Animals as natural geometers. *Cognitive biology: evolutionary and developmental perspectives on mind, brain and behaviour (eds Tommasi L., Nadel L., Peterson M.)*, 83-104.

Vargas, J. P., López, J. C., Salas, C., & Thinus-Blanc, C. (2004). Encoding of geometric and featural spatial information by goldfish (Carassius auratus). *Journal of Comparative Psychology*, *118*(2), 206.

Von Saint Paul, U. (1982). Do geese use path integration for walking home?. In *Avian navigation* (pp. 298-307). Springer, Berlin, Heidelberg.

Wang, R. F., & Spelke, E. S. (2002). Human spatial representation: Insights from animals. *Trends in cognitive sciences*, *6*(9), 376-382.

Watson, J. B., and Lashley, K. S. (1915). Homing and related activities of birds, pp. 9-60.

Carnegie Institute, Washington, D.C.

Winkler-Rhoades N., Carey S.C., Spelke E.S., (2013). Two-year-old children interpret abstract, purely geometric maps, *Developmental Science*, 16:3, 365- 376.

Wystrach, A., & Beugnon, G. (2009). Ants learn geometry and features. *Current Biology*, *19*(1), 61-66.

Worsley, C. L., Recce, M., Spiers, H. J., Marley, J., Polkey, C. E., & Morris, R. G. (2001). Path integration following temporal lobectomy in humans. *Neuropsychologia*, *39*(5), 452-464.

Yousif, S. R., & Lourenco, S. F. (2017). Are all geometric cues created equal? Children’s use of distance and length for reorientation. *Cognitive Development*, *43*, 159-169.

Zugaro, M. B., Berthoz, A., & Wiener, S. I. (2001). Background, but not foreground, spatial cues are taken as references for head direction responses by rat anterodorsal thalamus neurons. *The Journal of Neuroscience*.