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

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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 surfaces in early spatial coding 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

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 in disoriented rats who searched for a previously seen target in accord with the geometric shape of the arena, despite the presence of other visual and olfactory cues (Cheng, 1986). For instance, if the target was in one corner of a rectangular arena, rats searched for it in the correct corner and its diagonally opposite corner (geometrically equivalent) with the same frequency (see Fig. 1 for an illustration of what we mean by "correct" and "geometric equivalent" corners). Sensitivity to geometric boundary structure in navigation has since then been observed across many distantly related species – from fish, 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 (Hermer

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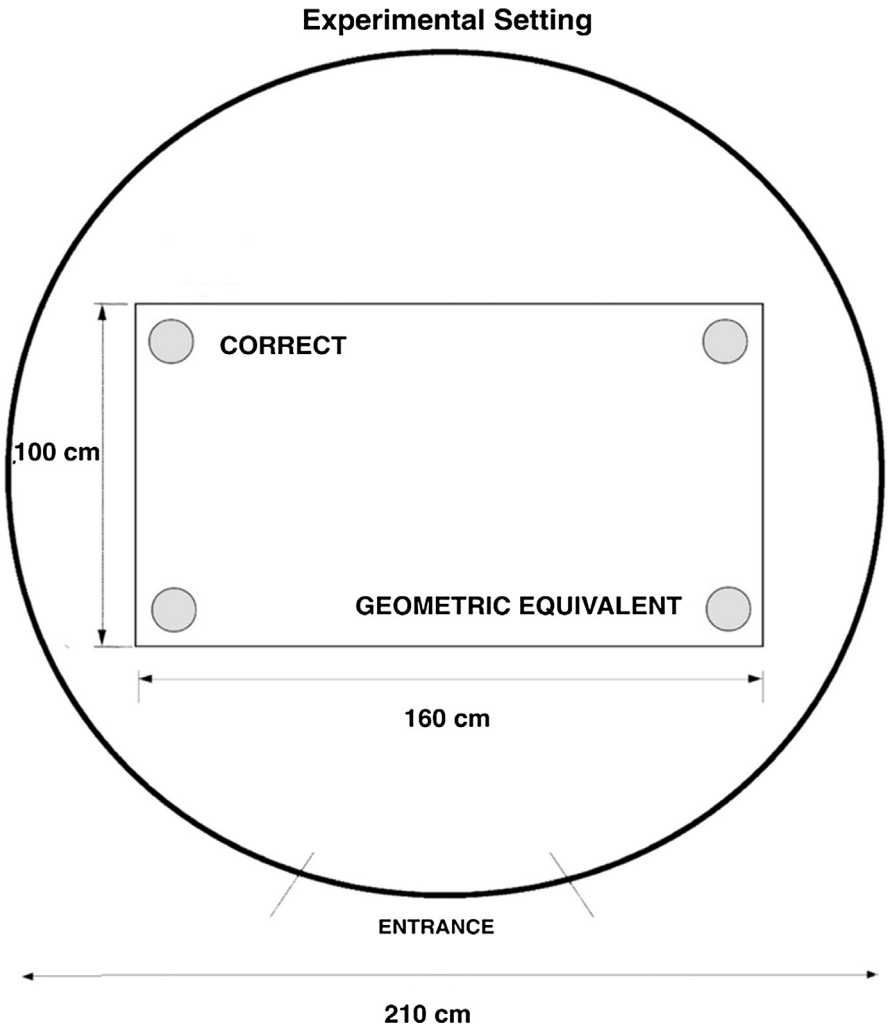

Fig. 1. Experimental setting, schematic view from above. If the sticker was placed in the northwest corner (labeled "correct"), the diagonally opposite southeast corner (labeled "geometric equivalent") is indistinguishable from the correct corner for disoriented subjects. Therefore, a proportion of correct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

& 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), the use of boundary layout is found consistently across studies (Lee, 2017). Therefore, while there has been substantial debate among developmental psychologists regarding the degree of domain specificity in 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

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