



What Do We Know about Navigation Development from the Perspective of Cognitive Neuroscience in Humans?

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Abstract Our ability to navigate through the environment forms the bedrock of many of our essential, everyday behaviors. Given this ecological importance, it is perhaps not surprising that we have dedicated neural tissue supporting navigation, including the hippocampus and entorhinal cortex in the medial temporal lobe (MTL) as well as the retrosplenial complex (RSComp) (also known as the medial place area), occipital place area (OPA), and superior parietal lobule (SPL) in neocortex. Recently, it has been proposed that each of these regions may support a distinct role in adult human navigation, with MTL and RSComp involved in “map-based navigation” and OPA and SPL involved in “visually guided navigation.” Despite advances in understanding how these brain regions support navigation in adulthood, surprisingly little is known about how they develop. To address this gap, the limited body of literature on the development of MTL and RSComp, and their involvement in map-based navigation, is reviewed in this chapter. In addition, a novel, and perhaps counterintuitive, hypothesis is proposed; namely, that map-based navigation (including MTL and RSComp) emerges early, by at least five years of age. Thereafter, the few studies available on the development of OPA and its involvement in visually guided navigation are reviewed, and a further hypothesis is advanced that OPA and its involvement in visually navigation develops late, possibly in a discontinuous manner, and does not emerge until around eight years of age.

Keywords Spatial development, brain imaging, higher level vision, scene processing, pediatric fMRI

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1 Introduction

Over the past three decades, cognitive neuroscience research has uncovered several key brain regions that support navigation in adult humans, including the hippocampus and entorhinal cortex in the MTL, as well as three cortical regions: the RSComp (Maguire 2001), the OPA (Dilks et al. 2013), and the SPL (Yoon et al. 2025). Beyond establishing the general involvement of these structures in navigation, however, recent functional magnetic resonance imaging (fMRI) research suggests that each of these regions may play a distinct role within the broader domain of navigation (Dilks et al. 2022).

More specifically, MTL and RSComp—also referred to as the medial place area (Silson et al. 2016)—have been implicated in “map-based navigation,” which is the ability to travel from a specific location to distant place (e.g., from your house to a favorite restaurant across town). These brain regions represent information necessary for map-based navigation, including location, orientation, distance, borders and boundaries, landmarks, and spatial layout (for reviews, see Dilks et al. 2022 and Chapter 9). By contrast, it has been proposed that OPA and SPL are involved in a distinct form of navigation, referred to as “visually guided navigation”—the ability to move about the immediately visible environment while avoiding boundaries and obstacles, such walking around a kitchen without bumping into the cabinets or the kitchen table (Dilks et al. 2022). Indeed, both OPA and SPL represent information necessary for visually guided navigation, including egocentric “sense” information (i.e., left/right orientation) (Dilks et al. 2011; Yoon et al. 2025) and first-person perspective motion information through scenes that mimic the visual experience of navigating through immediately visible environments (Kamps et al. 2016; Yoon et al. 2025). Moreover, OPA and SPL are preferentially functionally connected to each other (Yoon et al. 2025). Critically, however, OPA does not represent information necessary for map-based navigation (i.e., location and orientation) (Persichetti and Dilks 2019), and SPL has not yet been explicitly tested on this information. Finally, studies investigating the “function” of these regions, not just the information represented, found that OPA and SPL show greater activation when participants are engaged in a visually guided navigation task compared to two control tasks, a pattern not seen in MTL and RSComp (Persichetti and Dilks 2018; Yoon et al. 2025). Yet, despite this growing understanding about how MTL, RSComp, OPA, and SPL support navigation in adult humans, we know shockingly little about how these systems develop. So, how do these brain regions develop?

After reviewing what little is known about the development of MTL and RSComp and their involvement in map-based navigation, we offer the novel, perhaps counterintuitive, hypothesis that map-based navigation (including MTL and RSComp) emerges early in life—by at least five years of age, if not earlier. We then discuss the few available studies on the development of OPA, which suggest that OPA and its involvement in visually guided navigation develop surprisingly late, not until around eight years of age. Further, we propose that OPA and its involvement in visually guided navigation develops discontinuously. Finally, since studies have not yet investigated the development of SPL and its involvement in visually guided navigation, future research is needed.

2 The Early Development of MTL and Its Involvement in Map-Based Navigation

Despite the well-established developmental models of MTL in animals (for a review, see [Chapter 8](#)), how MTL begins to support map-based navigation in humans remains largely unknown. Instead, the developmental trajectory of hippocampus has been studied in terms of its structure and connectivity to the rest of the brain, and findings suggest a prolonged development. For example, the volume of the hippocampus continues to change until approximately 15 years of age (Daugherty et al. 2016; Gogtay et al. 2006; Krogsrud et al. 2014). Likewise, functional connectivity between the hippocampus and other cortical regions continues to mature throughout late childhood (DeMaster et al. 2014). In line with these anatomical and connectivity findings, numerous behavioral studies have suggested prolonged development in map-based navigation and related abilities presumably supported by MTL (Burles et al. 2020; Cousins et al. 1983; Lehnung et al. 2003; Nazareth et al. 2018; Overman et al. 1996). A child's ability to encode and utilize landmarks, for example, improves between the ages of 6–10 years (Allen et al. 1979; Cohen and Schuepfer 1980; Jansen-Osmann and Wiedenbauer 2004; Nys et al. 2015), and it is still not adultlike even at age 10 (Allen et al. 1979; Cohen and Schuepfer 1980). Furthermore, route learning (i.e., the acquisition of sequential or metric information between landmarks) and path-integration skills in seven- to ten-year-olds are less developed than those of adults (Allen et al. 1979; Burles et al. 2020; Cohen and Schuepfer 1980; Cousins et al. 1983; Nazareth et al. 2018). Together, these behavioral studies provide indirect evidence supporting the hypothesis that the MTL may develop quite late in childhood.

More direct evidence in support of this hypothesis comes from a recent behavioral study that adapted a virtual environment paradigm from an adult fMRI study that was aimed at investigating the role of hippocampus in map-based navigation (Doeller et al. 2008). In that study, which used a virtual large-scale space with unique geometry and landmark objects, Doeller et al. (2008) found that the hippocampus was involved in geometry-based (or boundary-based) learning of the environment, while the dorsal striatum was involved in landmark- or object-based learning. Using this same paradigm, Julian et al. (2019) behaviorally tested six- to ten-year-old children on geometry- versus landmark-based learning. They found that children, compared to adults, were worse at geometry-based learning but not landmark-based learning, which suggests that geometry-based learning (supported by the hippocampus) matures later than landmark-based learning (supported by the dorsal striatum). Although these behavioral measures serve only as proxies for neural development, they nevertheless provide more direct evidence for the hypothesis that map-based navigation supported by MTL undergoes prolonged development.

However, the prolonged development of the hippocampal structure, its connectivity, and even map-based navigation abilities themselves does *not* necessarily mean that the hippocampus was not involved in map-based navigation earlier in life. Indeed, in a recent fMRI study with five-year-old children (Jung and Dilks 2025), we directly examined the “function” of the developing hippocampus and demonstrated that the hippocampus is, in fact, involved in map-based navigation *early* in childhood. Specifically, we created a virtual town, which children learned by navigating

through it via button presses. The town had three different “locations”: a mountain, a lake, and trees (see [Figure 7.1](#)), and each location contained two buildings, for a total of six buildings in the town. Each building was a specific type; there were two ice cream stores, two playgrounds, and two fire stations. Importantly, the location of any two buildings belonging to the same category was completely dissociable from the category information. For instance, if one ice cream store was in the mountain location, the other ice cream store was in the lake location. This design allowed us to characterize the neural response to buildings located in the same location (e.g., an ice cream store and a fire station both at the mountain location) separately from the neural response to buildings in the same category (e.g., ice cream stores regardless of location). We then asked whether the hippocampus in five-year-olds represents location information critical for map-based navigation and found that indeed the hippocampus (along with RSComp, see below) represents the location information of buildings. Thus, by at least five years of age, the hippocampus is able to support map-based navigation; this is consistent with animal models that have suggested the early development of the hippocampus (e.g., Wills et al. 2014). Interestingly, the hippocampus also represented category information of buildings, which is not particularly relevant for map-based navigation and may reflect its broader role in declarative memory and category learning (e.g., Eichenbaum 2000). Taken together, these findings provide the first direct neural evidence that the hippocampus in humans is involved in map-based navigation by at least age five, suggesting the early emergence of the hippocampal navigation system.

How then are we to reconcile this finding with the large body of behavioral literature (discussed above) that highlights the late development of map-based navigation skills? It is important to note that most, if not all, of these studies focused on when children’s navigation abilities reach full maturity (i.e., when they become adult-like) rather than on when these abilities first emerge. In fact, studies investigating younger children have shown that certain foundational skills, such as landmark recognition, begin to emerge relatively early, around five years of age (Acredolo 1977; Herman and Siegel 1978), consistent with our finding that the hippocampus represents location information at this age. Therefore, we hypothesize that map-based navigation (including the hippocampus) emerges relatively early in life, by around five years of age, if not earlier, and undergoes subsequent refinement as children

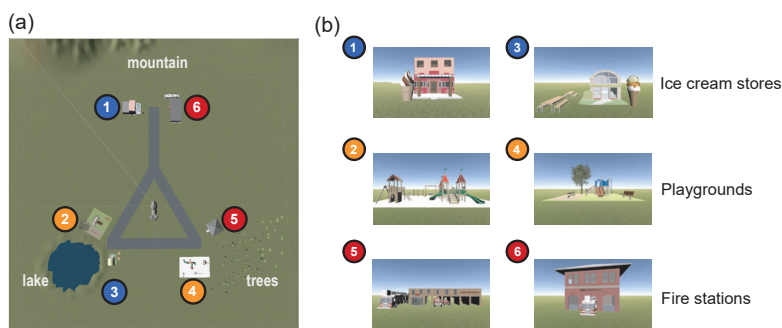


Figure 7.1 (a) An aerial view of the virtual town. Six buildings are placed in either the mountain, lake, or tree locations. (b) Each building belongs to one of three categories: ice cream store (1 and 3), playground (2 and 4), and fire station (5 and 6). Note the children never saw the aerial view of the town. Figure from Jung and Dilks (2025), used with permission.

gain more experience and acquire more advanced map-based navigational skills (e.g., route learning, integration of landmark and route). Future research, however, is needed to clarify how continued development of the hippocampus supports such refinement in children's map-based navigational abilities.

3 The Early Development of RSComp and Its Involvement in Map-Based Navigation

To date, no studies have directly examined how RSComp begins to support map-based navigation, although many have assumed that, like the hippocampus, it undergoes prolonged development (Burles et al. 2020; Cousins et al. 1983; Lehnung et al. 2003; Nazareth et al. 2018; Overman et al. 1996). Our recent research challenges this idea, revealing that RSComp, like hippocampus, develops much earlier than previously assumed (Jung and Dilks 2025).

In this work (Jung and Dilks 2025), again using fMRI and a virtual town paradigm (see [Figure 7.1](#)), we tested whether RSComp, like hippocampus, represents the location of specific places (i.e., information necessary for map-based navigation). Similar to the findings in adults (Persichetti and Dilks 2019), where RSComp represents location information but not category information (i.e., information *not* necessary for map-based navigation), we found that in five-year-old children, RSComp also represents location information, but not category information. By contrast, the parahippocampal place area—another cortical region that is scene selective (like RSComp), not involved in map-based navigation, but involved in scene categorization—showed the exact opposite pattern, representing category information but not location information. These findings suggest that the map-based navigation supported by RSComp develops early, emerging by at least age five, if not earlier.

4 The Late Development of OPA and Its Involvement in Visually Guided Navigation

Children begin to move about their immediately visible environments relatively early in life. At around 7–12 months they begin to crawl and progress to walking around 9–18 months (Newcombe 2019). This early behavioral emergence of locomotion skills often leads to the intuition that visually guided navigation would mature relatively early in childhood. Recent fMRI work in children (Jung et al. 2024; Kamps et al. 2020), however, suggests that OPA develops surprisingly late in childhood. The information necessary for visually guided navigation is not even represented at five years of age; it only emerges around eight years of age.

One of the first studies to support the hypothesis that OPA is late developing comes from an fMRI study in adults. In this study, we asked whether OPA represents visual information about crawling and walking—the two types of locomotion by which humans move about their immediately visible environment (Jones et al. 2023). Interestingly, we found that OPA does *not* represent visual information about

crawling at all, showing similar response to videos from a crawling perspective and to two other videos depicting perspectives by which humans do not or cannot move about the immediately visible environment (i.e., “flying” and “scrambled” videos). Rather, OPA represents visual information from a walking perspective only, showing a greater response to the videos from a walking perspective than to any of the other videos, including crawling. These results suggest that OPA may never have supported crawling and develops only after children begin to walk. Following up on this finding, a recent fMRI study conducted on two groups of children who know how to walk (i.e., five- and eight-year-olds) revealed that OPA only shows “walking selectivity” (i.e., the greater response to the walking videos than to any of the others, including crawling) in eight-year-olds, but not in five-year-olds. This finding further supports the hypothesis that OPA is late developing and suggests that OPA develops only after a child is walking like an adult (Jung et al. 2024). Similarly, another fMRI study conducted on children in this same age range demonstrated that OPA does not represent first-person perspective motion information through scenes in five-year-olds, and only does so in 8-year-olds (Kamps et al. 2020). Taken together, these results suggest that OPA undergoes protracted development; walking selectivity and first-person perspective motion selectivity (information necessary for visually guided navigation) are not even present until around five years of age and are only detectable at around eight years of age.

The findings that OPA undergoes protracted development dovetails with several other behavioral findings. For example, in a recent behavioral study, Kamps et al. (2023) tested the development of visually guided navigation and scene categorization abilities in children between four and nine years of age and found that visually guided navigation is slower to develop (adultlike performance is not reached until around eight years of age) compared to scene categorization (adultlike performance is reached around five years of age). Finally, obstacle avoidance and efficient path taking—two key features of visually guided navigation—develop slowly, again not reaching adultlike levels until around age eight (Berard and Vallis 2006; Choi et al. 2016; Michel et al. 2010; Pryde et al. 1997).

At the same time, and as alluded to above, humans begin moving around their environment early in life (e.g., crawling at approximately nine months) and show remarkably sophisticated navigational ability within the first few years (Newcombe 2019). For example, young children can use boundaries to recover their orientation after becoming disoriented (Hermer and Spelke 1994), and infants understand whether it is safe to locomote over a “visual cliff” (Gibson and Walk 1960). How, then, can we reconcile these observations with the hypothesis that visually guided navigation undergoes protracted development? One possibility is that these tasks rely on qualitatively different systems. For example, the reorientation task may involve spatial memory systems in the hippocampus, whereas the visual cliff task may depend on basic depth perception in early visual cortex. Another possibility is that these tasks rely on the same visually guided navigation system (i.e., OPA or perhaps even SPI), and that despite development extending well into childhood, the foundations of this system are nevertheless intact early and sufficient to support these early navigational behaviors (discussed further below).

What then drives such late development of OPA? One possibility is that the cortical connectivity of OPA to primary visual cortex (V1), which enables OPA

to receive visual information in the first place, undergoes protracted development. More specifically, given that peripheral vision is important for visually guided navigation (Cao and Händel 2019; Franchak and Adolph 2010; Stoffregen et al. 1987), the connectivity between OPA and the region of V1, which represents the peripheral visual field, may develop late in childhood. Using both behavior and neural data, our group is currently investigating this exact question, asking (a) when children begin to use peripheral vision for visually guided navigation and (b) when their OPA shows connectivity to “peripheral” V1. Preliminary data reveal the following:

- Eight-year-olds, like adults, use peripheral vision to perform a visually guided navigation task. Five-year-olds, however, do *not*; instead, they use central vision.
- The functional connectivity between OPA and peripheral V1 is present only in eight-year-olds (like adults), not in five-year-olds.

These findings support the hypothesis that the late development of cortical connectivity between OPA and peripheral V1 may drive the late development of OPA. They also strongly support the hypothesis that OPA (and visually guided navigation) is late developing.

Does this mean then that OPA is not involved in visually guided navigation *at all* until around eight years of the age? Since, at age five, OPA does not represent at least two kinds of navigationally relevant information (i.e., visual information from a walking perspective and first-person perspective motion information), we are left with the fascinating possibility that OPA develops abruptly (or discontinuously) only at around age eight, and not beforehand. Future research is required to address this possibility, as it could still be the case that OPA supports visually guided navigation before age eight (at five years of age even) and develops continuously with earlier emerging representations of more “primitive” kinds of navigationally relevant information (e.g., sense and egocentric distance information). Indeed, studies have shown that young toddlers (Hermer and Spelke 1994) and even nonhuman species, including fish (Sovrano et al. 2002) and insects (Wehner et al. 1996), can perceive and utilize sense and egocentric distance information for navigation. Thus, the question remains: How does OPA develop—continuously or discontinuously? To approach this question, a recent study by our lab used fMRI adaptation to analyze whether OPA represents sense information at age five (Rennert and Dilks, *in press*). This data reveal that sense information is not at all represented in OPA in five-year-olds but is represented in eight-year-olds, consistent with the hypothesis that OPA develops discontinuously. Interestingly, preliminary data also reveal that sense information is represented in RSComp in five-year-olds (as well as eight-year-olds), consistent with the hypothesis that RSComp develops early.

5 Conclusion

Despite decades of research on navigation in the adult human brain, how these systems develop remains largely unknown. Here, we examined behavioral and fMRI studies on the development of the map-based navigation system, including MTL

and RSComp, as well as recent behavioral and fMRI studies on the development of the visually guided navigation system, focusing on OPA. Despite the anatomical and connectivity findings and behavioral work, which suggests that the map-based navigation system develops late (and is really revealed when the system is fully mature), a recent fMRI study found that MTL and RSComp are both involved in map-based navigation much earlier in life, by at least age five, if not before. By contrast, findings for OPA reveal a surprisingly late developmental trajectory, with no evidence of visually guided information processing until around age eight. This raises the intriguing possibility of discontinuous development. Taken together, these findings lead to the novel (and perhaps counterintuitive) developmental hypothesis that the visually guided navigation system (including OPA and perhaps SPL) develops later than the map-based navigation system (including MTL and RSComp).

Several important questions, however, remain. First, although human fMRI has illuminated the roles of RSComp, OPA, and SPL in navigation, very little is known about these systems in animal models. Future research is thus needed to examine how these cortical navigation systems function and develop in nonhuman species (if they even exist), which would provide critical mechanistic insight into the evolution and function of navigation systems across species. Second, while the development of MTL has been extensively studied in animals, relatively little is known about how these regions develop to support map-based navigation in humans. Understanding how the MTL emerges and potentially interacts with the cortical navigation regions (e.g., RSComp, and perhaps OPA and SPL) during development remains a central challenge for the field—one that will be essential for a comprehensive theory of navigation across both species and development.

Acknowledgments We would like to thank the Child Study Center at Emory for supporting recruitment efforts and the Facility for Education and Research in Neuroscience (FERN) at Emory University for providing neuroimaging resources. Finally, we would like to thank all of the children and their families who participated in these studies.

References

- Acredolo LP (1977) Developmental Changes in the Ability to Coordinate Perspectives of a Large-Scale Space. *Dev Psychol* 13 (1):1–8. <https://doi.org/10.1037/0012-1649.13.1.1>
- Allen GL, Kirasic KC, Siegel AW, and Herman JF (1979) Developmental Issues in Cognitive Mapping: The Selection and Utilization of Environmental Landmarks. *Child Dev* 50 (4):1062–1070. <https://doi.org/10.2307/1129332>
- Berard JR, and Vallis LA (2006) Characteristics of Single and Double Obstacle Avoidance Strategies: A Comparison between Adults and Children. *Exp Brain Res* 175 (1):21–31. <https://doi.org/10.1007/s00221-006-0529-0>
- Burles F, Liu I, Hart C, et al. (2020) The Emergence of Cognitive Maps for Spatial Navigation in 7- to 10-Year-Old Children. *Child Dev* 91 (3):e733–e744. <https://doi.org/10.1111/cdev.13285>
- Cao L, and Händel B (2019) Walking Enhances Peripheral Visual Processing in Humans. *PLoS Biol* 17 (10):e3000511. <https://doi.org/10.1371/journal.pbio.3000511>

- Choi JT, Jensen P, and Nielsen JB (2016) Locomotor Sequence Learning in Visually Guided Walking. *J Neurophysiol* 115 (4):2014–2020. <https://doi.org/10.1152/jn.00938.2015>
- Cohen R, and Schupfer T (1980) The Representation of Landmarks and Routes. *Child Dev* 51 (4):1065–1071. <https://psycnet.apa.org/doi/10.2307/1129545>
- Cousins JH, Siegel AW, and Maxwell SE (1983) Way Finding and Cognitive Mapping in Large-Scale Environments: A Test of a Developmental Model. *J Exp Child Psychol* 35 (1):1–20. [https://doi.org/10.1016/0022-0965\(83\)90066-8](https://doi.org/10.1016/0022-0965(83)90066-8)
- Daugherty AM, Bender AR, Raz N, and Ofen N (2016) Age Differences in Hippocampal Subfield Volumes from Childhood to Late Adulthood. *Hippocampus* 26 (2):220–228. <https://doi.org/10.1002/hipo.22517>
- DeMaster D, Pathman T, Lee JK, and Ghetti S (2014) Structural Development of the Hippocampus and Episodic Memory: Developmental Differences Along the Anterior/Posterior Axis. *Cereb Cortex* 24 (11):3036–3045. <https://doi.org/10.1093/cercor/bht160>
- Dilks DD, Julian JB, Kubilius J, Spelke ES, and Kanwisher N (2011) Mirror-Image Sensitivity and Invariance in Object and Scene Processing Pathways. *J Neurosci* 31 (31):11305–11312. <https://doi.org/10.1523/JNEUROSCI.1935-11.2011>
- Dilks DD, Julian JB, Paunov AM, and Kanwisher N (2013) The Occipital Place Area Is Causally and Selectively Involved in Scene Perception. *J Neurosci* 33 (4):1331–1336. <https://doi.org/10.1523/JNEUROSCI.4081-12.2013>
- Dilks DD, Kamps FS, and Persichetti AS (2022) Three Cortical Scene Systems and Their Development. *Trends Cogn Sci* 26 (2):117–127. <https://doi.org/10.1016/j.tics.2021.11.002>
- Doeller CF, King JA, and Burgess N (2008) Parallel Striatal and Hippocampal Systems for Landmarks and Boundaries in Spatial Memory. *PNAS* 105 (15):5915–5920. <https://doi.org/10.1073/pnas.0801489105>
- Eichenbaum H (2000) A Cortical-Hippocampal System for Declarative Memory. *Nat Rev Neurosci* 1:41–50. <https://doi.org/10.1038/35036213>
- Franchak JM, and Adolph KE (2010) Visually Guided Navigation: Head-Mounted Eye-Tracking of Natural Locomotion in Children and Adults. *Vision Res* 50 (24):2766–2774. <https://doi.org/10.1016/j.visres.2010.09.024>
- Gibson EJ, and Walk RD (1960) The “Visual Cliff.” *Sci Am* 202 (4):64–71. <https://psycnet.apa.org/doi/10.1038/scientificamerican0460-64>
- Gogtay N, Nugent III TF, Herman DH, et al. (2006) Dynamic Mapping of Normal Human Hippocampal Development. *Hippocampus* 16 (8):664–672. <https://doi.org/10.1002/hipo.20193>
- Herman JF, and Siegel AW (1978) The Development of Cognitive Mapping of the Large-Scale Environment. *J Exp Child Psychol* 26 (3):389–406. [https://doi.org/10.1016/0022-0965\(78\)90120-0](https://doi.org/10.1016/0022-0965(78)90120-0)
- Hermer L, and Spelke ES (1994) A Geometric Process for Spatial Reorientation in Young Children. *Nature* 370 (6484):57–59. <https://doi.org/10.1038/370057a0>
- Jansen-Osmann P, and Wiedenbauer G (2004) The Representation of Landmarks and Routes in Children and Adults: A Study in a Virtual Environment. *J Environ Psychol* 24 (3):347–357. <https://doi.org/10.1016/j.jenvp.2004.08.003>
- Jones CM, Byland J, and Dilks DD (2023) The Occipital Place Area Represents Visual Information about Walking, Not Crawling. *Cereb Cortex* 33 (12):7500–7505. <https://doi.org/10.1093/cercor/bhad055>
- Julian JB, Kamps FS, Epstein RA, and Dilks DD (2019) Dissociable Spatial Memory Systems Revealed by Typical and Atypical Human Development. *Dev Sci* 22 (2):e12737. <https://doi.org/10.1111/desc.12737>
- Jung Y, and Dilks DD (2025) Early Development of Navigationally Relevant Location Information in the Retrosplenial Complex. *PNAS* 122 (19):e2503569122. <https://doi.org/10.1073/pnas.2503569122>

- Jung Y, Hsu D, and Dilks DD (2024) “Walking Selectivity” in the Occipital Place Area in 8-Year-Olds, Not 5-Year-Olds. *Cereb Cortex* 34 (3):bhac101. <https://doi.org/10.1093/cercor/bhae101>
- Kamps FS, Lall V, and Dilks DD (2016) The Occipital Place Area Represents First-Person Perspective Motion in Formation through Scenes. *Cortex* 83:17–26. <https://doi.org/10.1016/j.cortex.2016.06.022>
- Kamps FS, Pincus JE, Radwan SF, Wahab S, and Dilks DD (2020) Late Development of Navigationally Relevant Motion Processing in the Occipital Place Area. *Curr Biol* 30 (3):544–550.e543. <https://doi.org/10.1016/j.cub.2019.12.008>
- Kamps FS, Rennert RJ, Radwan SF, et al. (2023) Dissociable Cognitive Systems for Recognizing Places and Navigating through Them: Developmental and Neuropsychological Evidence. *J Neurosci* 43 (36):6320–6329. <https://doi.org/10.1523/JNEUROSCI.0153-23.2023>
- Krogstad SK, Tamnes CK, Fjell AM, et al. (2014) Development of Hippocampal Subfield Volumes from 4 to 22 Years. *Hum Brain Mapp* 35 (11):5646–5657. <https://doi.org/10.1002/hbm.22576>
- Lehmann M, Lepow B, Ekroll V, et al. (2003) The Role of Locomotion in the Acquisition and Transfer of Spatial Knowledge in Children. *Scand J Psychol* 44 (2):79–86. <https://doi.org/10.1111/1467-9450.00324>
- Maguire EA (2001) The Retrosplenial Contribution to Human Navigation: A Review of Lesion and Neuroimaging Findings. *Scand J Psychol* 42 (3):225–238. <https://doi.org/10.1111/1467-9450.00233>
- Michel J, Grobet C, Dietz V, and Hedel HJA (2010) Obstacle Stepping in Children: Task Acquisition and Performance. *Gait Posture* 31 (3):341–346. <https://doi.org/10.1016/j.gaitpost.2009.12.001>
- Nazareth A, Weisberg SM, Margulis K, and Newcombe NS (2018) Charting the Development of Cognitive Mapping. *J Exp Child Psychol* 170:86–106. <https://doi.org/10.1016/j.jecp.2018.01.009>
- Newcombe NS (2019) Navigation and the Developing Brain. *J Exp Biol* 222 (Suppl_1):jeb186460. <https://doi.org/10.1242/jeb.186460>
- Nys M, Gyselinck V, Orriols E, and Hickmann M (2015) Landmark and Route Knowledge in Children’s Spatial Representation of a Virtual Environment. *Front Psychol* 5:fpsyg.2014.01522. <https://doi.org/10.3389/fpsyg.2014.01522>
- Overman WH, Pate BJ, Moore K, and Peuster A (1996) Ontogeny of Place Learning in Children as Measured in the Radial Arm Maze, Morris Search Task, and Open Field Task. *Behav Neurosci* 110 (6):1205–1228. <https://doi.org/10.1037//0735-7044.110.6.1205>
- Persichetti AS, and Dilks DD (2018) Dissociable Neural Systems for Recognizing Places and Navigating through Them. *J Neurosci* 38 (48):10295–10304. <https://doi.org/10.1523/JNEUROSCI.1200-18.2018>
- (2019) Distinct Representations of Spatial and Categorical Relationships across Human Scene-Selective Cortex. *PNAS* 116 (42):21312–21317. <https://doi.org/10.1073/pnas.1903057116>
- Pryde KM, Roy EA, and Patla AE (1997) Age-Related Trends in Locomotor Ability and Obstacle Avoidance. *Hum Mov Sci* 16 (4):507–516. [https://doi.org/10.1016/S0167-9457\(96\)00064-4](https://doi.org/10.1016/S0167-9457(96)00064-4)
- Rennert RJ and Dilks DD (in press). Two Cortical Navigation Systems and Their Development. *Cerebral Cortex*, in press. <https://doi.org/10.1093/cercor/bhaf326>
- Silson E, Steel A, and Baker C (2016) Scene-Selectivity and Retinotopy in Medial Parietal Cortex. *Front Hum Neurosci* 10:412. <https://doi.org/10.3389/fnhum.2016.00412>
- Sovrano VA, Bisazza A, and 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. [https://doi.org/10.1016/S0010-0277\(02\)00110-5](https://doi.org/10.1016/S0010-0277(02)00110-5)

- Stoffregen TA, Schmuckler MA, and Gibson EJ (1987) Use of Central and Peripheral Optical Flow in Stance and Locomotion in Young Walkers. *Perception* 16 (1):113–119. <https://doi.org/10.1068/p160113>
- Wehner R, Michel B, and Antonsen P (1996) Visual Navigation in Insects: Coupling of Egocentric and Geocentric Information. *J Exp Biol* 199 (Pt 1):129–140. <https://doi.org/10.1242/jeb.199.1.129>
- Wills TJ, Muessig L, and Cacucci F (2014) The Development of Spatial Behaviour and the Hippocampal Neural Representation of Space. *Philos Trans R Soc Lond B Biol Sci* 369 (1635):20130409. <https://doi.org/10.1098/rstb.2013.0409>
- Yoon HK, Jung Y, Persichetti AS, and Dilks DD (2025) A Scene-Selective Region in the Superior Parietal Lobule for Visually Guided Navigation. *Cereb Cortex* 35 (4):bhaf082. <https://doi.org/10.1093/cercor/bhaf082>

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