CHAPTER EIGHT

Harnessing technology to measure individual differences in spatial thinking in early childhood from a relational developmental systems perspective

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Abstract

According to the *Relational Developmental Systems* perspective, the development of individual differences in spatial thinking (e.g., mental rotation, spatial reorientation, and spatial language) are attributed to various psychological (e.g., children's cognitive strategies), biological (e.g., structure and function of hippocampus), and cultural systems (e.g., caregiver spatial language input). Yet, measuring the development of individual differences in spatial thinking in young children, as well as the psychological, biological, and cultural systems that influence the development of these abilities, presents unique challenges. The current paper outlines ways to harness available technology including eye-tracking, eye-blink conditioning, MRI, Zoom, and LENA technology, to study the development of individual differences in young children's spatial thinking. The technologies discussed offer ways to examine children's spatial thinking development from different levels of analyses (i.e., psychological, biological, cultural), thereby allowing us to advance the study of developmental theory. We conclude with a discussion of the use of artificial intelligence.

Spatial thinking involves the "processing, comparing, transforming, and representation of spatial information" (p. 567, Hodgkiss, Gilligan-Lee, Thomas, Tolmie, & Farran, 2021). Spatial thinking is crucial for performing various daily tasks like packing a suitcase, finding your parked car in a lot, navigating city streets, reading a map, recalling patterns, and discerning shapes, sizes, and other spatial features of objects (Pruden et al., 2020). Research exploring the development of spatial thinking has gained momentum in the last 20 years, in part because individual differences in spatial ability predict interest, engagement and success in science, technology, engineering, and mathematics (STEM) disciplines (Shea, Lubinski, & Benbow, 2001; Wai, Lubinski, & Benbow, 2009), and also because spatial thinking has been shown to be malleable to training and intervention (e.g., Terlecki, Newcombe, & Little, 2008; Uttal et al., 2013).

Research consistently shows, across different samples, methodological designs and using different stimuli and tasks, that young children *vary* widely in their spatial skills. Indeed, these individual differences are seen across *different types* of spatial skills, including mental rotation (e.g., Beckner et al., 2023; Frick, Hansen, & Newcombe, 2013; Frick, Möhring, & Newcombe, 2014; Levine, Huttenlocher, Taylor, & Langrock, 1999; Pedrett, Chavaillaz, & Frick, 2023; Pruden, Levine, & Huttenlocher, 2011; Ralph, Berinhout, & Maguire, 2021), spatial reorientation (e.g., Gouteux, Vauclair, & Thinus-Blanc, 2001; Hupbach & Nadel, 2005; Learmonth, Newcombe, Sheridan, & Jones, 2008; Smith et al., 2008; Vieites, Pruden, Shusterman, & Reeb-Sutherland, 2020), and the comprehension and production of spatial language (e.g., Hall et al., 2023; Odean et al., 2023; Pruden & Levine, 2017; Pruden et al., 2011; Ralph et al., 2021). *Mental rotation* is the ability to mentally rotate a 2- or 3-dimensional object in our mind without physically turning it (Shepard & Metzler, 1971). *Spatial reorientation* is the ability to re-establish one's sense of position after becoming lost or disoriented (Julian, Keinath, Marchette, & Epstein, 2018). *Spatial language* is the basis of understanding and describing with words the relations between objects, their location in the environment, and their size, shape, and other spatial features (Pruden & Odean, 2017). Together, these skills make up a host of important spatial abilities that researchers have been paying particular attention to in early childhood between the ages of 3- and 6 -years-old, as this appears to be a critical developmental timepoint during which individual differences begin to emerge (e.g., Abad, Odean, & Pruden, 2018; Frick et al., 2013; Lauer, Yhang, & Lourenco, 2019). With decades of research showing evidence of *when* these various spatial abilities develop, many have turned to asking *how* individual differences in spatial thinking develop.

1. Relational developmental systems perspective as a framework for the study of individual differences in young children's spatial thinking

We have been approaching the study of *how* individual differences in young children's spatial thinking develop from a Relational Developmental

Systems (RDS) perspective. An RDS perspective proposes that development is best explained by the co-acting of multiple systems operating at various levels of analyses (i.e., the psychological, biological, and cultural) over time to produce change in thinking and abilities (Overton, 2014; Pruden et al., 2020). For example, we had previously written about how individual differences in emerging adults' mental rotation abilities could be studied from a psychological level of analysis or lens by examining what the individual brings to their own development via their cognitive and affective systems (Pruden et al., 2020). Specifically, we had argued that development of individual differences in mental rotation ability could be explained, in part, by one's cognitive strategy for solving mental rotation problems, by one's executive functions, and by one's level of spatial anxiety. Similarly, we argued that if a researcher used the biological level of analyses or lens to approach the study of individual differences in mental rotation then relevant systems for further study would be specific biological systems, like the hippocampus and other medial temporal lobe regions. Finally, we had previously argued that a researcher taking a cultural level of analysis or lens might approach the study of individual differences in mental rotation by examining systems such as caregiver language input or exposure to spatial play and spatial toys.

Grounded in developmental theory, the *RDS* perspective, we have been able to generate many specific, testable research questions related to how individual differences in young children's spatial thinking develops (e.g., Pruden & Odean, 2017; Pruden et al., 2020). The challenge, however, has been in overcoming methodological concerns and issues in working with young children between the ages of 3 and 6 years. Methodological concerns have included worries about children's ability to accurately self-report how they solve tasks given their limited vocabulary, limitations on young children's ability to complete tasks while in an MRI scanner, and disruptions to in-person data collection across all settings (i.e., lab, home, school, community) during a global pandemic. Technological advances in eye-tracking, eye-blink conditioning, structural magnetic resonance imaging (MRI), Zoom, and wearable devices like Language ENvironment Analysis (LENA), allow us to overcome the methodological concerns listed above. This technology serves as new measurement tools for the study of the proposed systems that explain individual differences in young children's spatial thinking. We explore each of these technological tools below with the aim of outlining how they can be leveraged to study the development of three different types of spatial skills: mental rotation, spatial reorientation, and spatial language. We then conclude by outlining how future studies may use these tools together, along with artificial intelligence, to study spatial thinking development within the RDS perspective.

2. A psychological level of analysis of children's mental rotation: measuring cognitive strategies with eye-tracking

Mental rotation is used to complete everyday tasks, like reading a map or putting Ikea furniture together, and in more difficult STEM tasks, like understanding pulley systems or reading MRI scans. Young children often use mental rotation skills to solve puzzles and even play matching or pattern games (Hall et al., 2023). There are reported links between children's mental rotation skills and their later academic success in science (Hodgkiss et al., 2018), mathematics (Gunderson, Ramirez, Beilock, & Levine, 2012), and language arts (Rutherford, Karamarkovich, & Lee, 2018). Given these important links to school success, many researchers now focus on *how* children solve mental rotation problems with the aim of understanding how to help children perform better on mental rotation tasks so that they may also later succeed in school subjects (Quaiser-Pohl, Rohe, & Amberger, 2010; Ralph, 2021).

A psychological level of analysis of children's mental rotation ability typically focuses on what cognitive or other conceptual or affective systems the child brings to the task at hand. We have been studying one candidate system, the *cognitive strategies,* that are used to solve mental rotation tasks. Below we discuss this system and how we have leveraged eye-tracking technology to overcome challenges in understanding the cognitive strategies that young children use to solve mental rotation tasks.

2.1 Mental rotation and children's cognitive strategies

Two cognitive strategies have been used to define *how* adults and more recently, young children solve mental rotation tasks (Nazareth et al., 2019); Rodriguez et al., 2024). The first strategy identified in literature is a *holistic strategy*. Using a holistic strategy, participants mentally rotate an object as a whole object (Pruden et al., 2020) when solving mental rotation tasks. The alternative strategy identified is a *piecemeal strategy*. Using a piecemeal strategy, participants successfully solve mental rotation tasks by identifying the individual parts or pieces of the object and matching those parts and

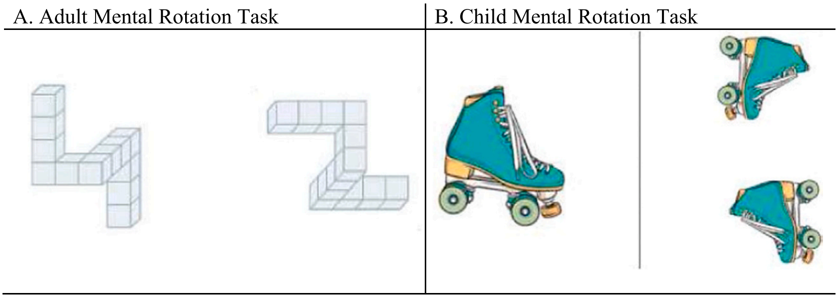

Fig. 1 *Sample of an adult and child mental rotation task*. *Note.* Fig. (A) represents an adult mental rotation task in which they are asked if the two images are the same (Nazareth, Killick, Dick, & Pruden, 2019). Fig. (B) is the Familiar Image Rotation Task used for children in which they are asked which small picture (top or bottom) is the same as the big picture (Rodriguez et al., 2024).

pieces to other object parts and pieces (Pruden et al., 2020). In a typical *adult* mental rotation task (see Fig. 1; Hegarty, 2018), participants are asked to verbally report how they solved the task as a way to evaluate which cognitive strategy they used. Adults who use a holistic strategy are reported as saying things like, "I turned the object until it matched," while those reported to use a piecemeal strategy are reported as saying things like, "this side has 3 cubes and this side 2 cubes."

Challenges do arise when asking young children to self-report how they solved a mental rotation task. Self-report typically requires some form of verbal response from the participant, which can be hard for young children that are still developing verbal skills (Chan & Von Baeyer, 2016). Further, young children also have a hard time self-reporting and monitoring their own problem-solving processing (Chan & Von Baeyer, 2016). Fortunately, previous work with adults (Nazareth et al., 2019) and more recent work with children (Rodriguez et al., 2024) finds certain eye gaze patterns map to one's cognitive strategy use. Thus, eye-tracking technology may be leveraged to overcome challenges in assessing cognitive strategy use in young children (Nazareth, Odean, & Pruden, 2017).

2.2 Eye-tracking technology

Eye-tracking technology is an inexpensive and non-invasive camera that uses near-infrared light to record eye movements (Geller, Winn, Mahr, & Mirman, 2020). The light sources in the eye tracker are almost invisible to the human eye and illuminate the eye so the camera can easily record the pupil. The light emitted is no greater than everyday exposure to sunlight and poses no risk to users. Some eye-trackers are screen based and can be mounted on a laptop or computer making it easy to travel with if data collection is outside a lab setting (i.e., a museum, at a preschool, at a library). Others can be worn like glasses for studies that may require movement (i.e., a navigation or wayfinding task). There are a variety of eye-trackers out on the market that can be purchased for research, including the Eyelink, the Tobii, and the Gazepoint systems. In this chapter, we will only be discussing video-based eye-trackers, but we do acknowledge that there are other types of devices that may also be suitable for use with young children (Hutton, 2019).

2.3 Eye-tracking data

Eye-trackers give large amounts of raw data depending on their sampling rates (Hutton, 2019). Deciding on an eye-tracker's sampling rate is important depending on the type of data a researcher is trying to collect. For example, in a study with 10 trials recorded for 10 s each using a 150 Hz sampling rate, 15,000 samples would have been recorded. That means the eye-tracker can record 150 eye-positions in one second. This is most useful for studies using changes in pupil size since the size of a pupil can change every millisecond (Bauer, Jost, Günther, & Jansen, 2022). A total of 15,000 samples of X and Y location points and durations can be an overwhelming amount of data to process. However, some eye-tracking software, like the Gazepoint GP3 software (Gazepoint, n.d.), simplify the information for users by calculating variables like, fixation counts, visit durations, and pupil sizes.

The data points that will be discussed in this section include fixation count, fixation duration, visit count, and visit duration (Rodriguez et al., 2024). Fixations are eye movements that shift below a calculated velocity threshold based on the sample's eye shifts. In other words, it is a pause in a person's eye gaze. Fixation counts are the number of fixations and fixation duration is the amount of time spent in a fixation. Visits are the movement between one fixation and a second fixation. In other words, is it the shift between two fixation points. Visit counts are the number of visits and visit duration is the time spent at visiting and revisiting points.

Eye-tracking software also provides a variety of visuals to better understand eye-gazes. The Gazepoint GP3 software provides video recordings of fixation maps, heat maps, opacity map, and bee swarms (see Fig. 2; Gazepoint, n.d.). A fixation map (Fig. 2A) uses circles to represent a fixation and lines to represent visits. The size of the circle indicates the fixation durations, and the lines represent visits. Researchers may find this most useful if they are

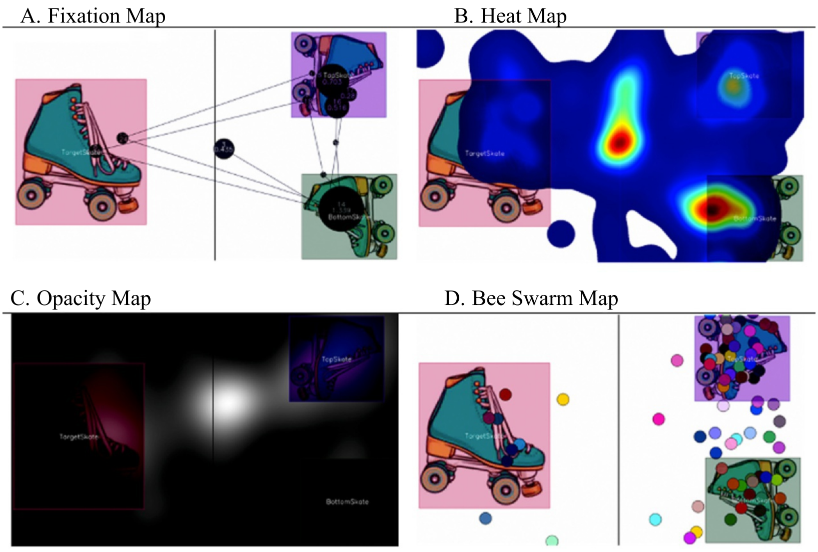

Fig. 2 *Gazepoint software eye-tracking output maps. Note.* Areas of Interest (AOI) are depicted by the color squares around the images and are defined by the researcher. Participants do not see the AOIs while testing. AOIs are only seen by researchers during data analysis.

interested in understanding the visual path an individual took during a cognitive task. The heat map (Fig. 2B) displays blobs of color that represent which areas of the stimuli were most often looked at, with warmer colors indicating greater time. Heat maps may be useful for researchers interested in understanding which sections of a stimulus were most intriguing to participants. Opacity maps (Fig. 2C) only illuminate the portion of the stimuli a participant fixated on most, like a spotlight. Researchers that are interested in understanding what drew participants' attention most may want to use opacity maps. A bee swarm map (Fig. 2D) can provide either individual or group level eye- movements. This is most useful for research that would like to visualize continuous visits for a single participant or for the entire sample.

2.4 Using eye-trackers to measure mental rotation

Prior work with adult participants has successfully used eye-tracking data points to link eye gaze patterns with the cognitive strategies participants use to solve a mental rotation task (Nazareth et al., 2019). In this study, a latent profile analysis (LPA) was conducted to determine if distinct groups can be identified using their fixation count, fixation duration, visit count, and visit duration.

The LPA identified two classes or groups, which align with the cognitive strategies participant's use to solve a mental rotation task. Class 1 was defined by fewer fixation counts and visit counts, and appear to map to a holistic strategy. Class 2 was defined by a higher number of fixation counts and visit counts, and appear to map to a piecemeal strategy.

In a similar study with children aged three to seven years old, eye-tracking data (i.e., fixation count, fixation duration, visit count, and visit duration) were used to conduct an LPA (Rodriguez et al., 2024). The Gazepoint GP3 eye-tracking system is lightweight and portable allowing for data collection in a science museum. The task environment of the Gazepoint GP3 eye-tracker and computer system in the museum can be seen in Fig. 3. The eye-tracker was positioned below the screen and placed about 24 in. away from the child's face. Each child needed to successfully calibrate before starting the child-friendly mental rotation task (Fig. 1B; task adapted from Fernández-Méndez, Contreras, & Elosúa, 2020). Children were instructed to play the "frozen game" during calibration and the task to ensure there was little movement. After successful calibration and a series of training trials, a total of 10 test trials were given. Children were asked to select from one of two images the image that was the same as the target image but rotated. Children's eye-movements were recorded during these test trials. Using the same analysis as (Nazareth et al., 2019) with adults, the LPA identified two classes or groups of children based on their fixation count, fixation duration, visit count, and visit duration data. Like adults, class 1 was defined by fewer fixation counts and visit counts and mapped to a holistic strategy. Class 2 was defined by a higher number of fixation counts and visit counts, and thus mapped to a piecemeal strategy. These results provide the first evidence that we can leverage eye-tracking technology to overcome obstacles in understanding how children solve mental rotation tasks. No verbal response is required to identify their strategy use, rather we can rely on their eye-gaze patterns.

2.5 Eye-tracking advantages

Prior to eye-tracking technology, most studies examining cognitive strategies relied on self-report (Hegarty, 2018; Quaiser-Pohl et al., 2010) or manual eye-tracking (Dean, Duhe, & Green, 1983) to measure the cognitive strategies used during mental rotation tasks. As previously mentioned, there are disadvantages to relying on self-report to measure young children's mental rotation. There are also notable disadvantages in manually eye-tracking gaze patterns that makes using eye-tracking technology a better option. Manual eye-tracking tends to be

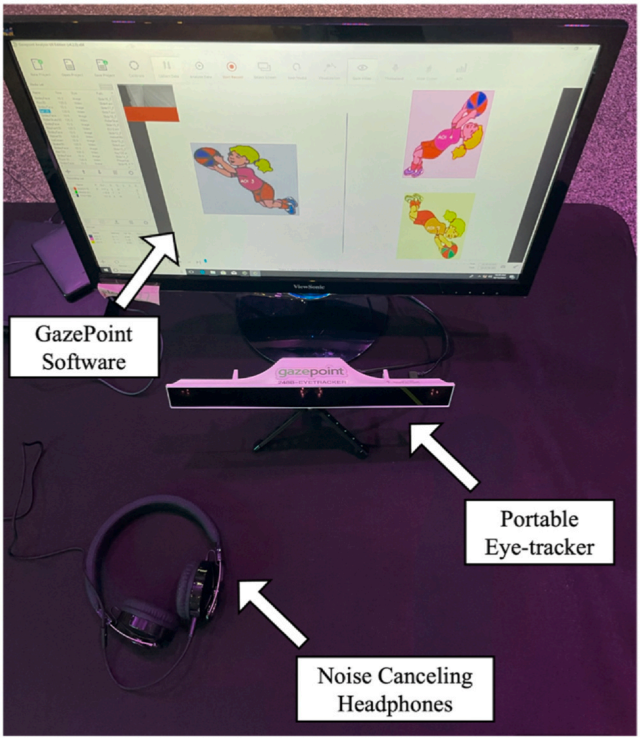

Fig. 3 *Eye-tracking task environment in a museum setting. Note.* A portable Gazepoint GP3 eye-tracking system can be used along with noise canceling headphones in different data collection settings including museums, preschools, and lab.

subjective, time intensive, and cannot record more detailed variables, like pupil sizes (Venker et al., 2020). Using an automated eye-tracking approach in studies that focus on cognition makes the data collection process and analysis faster, more precise, and automated. This approach is more objective than relying on self-report and manual eye-tracking (Quaiser-Pohl et al., 2010) or relying on accuracy data alone (Geiser, Lehmann, & Eid, 2006).

2.6 Eye-tracking limitations and recommendations

There are some limitations to consider when selecting the right technology to answer questions about the development of children's cognitive skills. First, most eye-trackers (except for head-mounted eye-trackers) work best when users are not moving their heads or bodies. Staying still may be especially difficult for young children. To overcome this limitation, Rodriguez and colleagues (2024) asked young children to play the "frozen game." By introducing this instruction as a game, children were more inclined to sit still and took joy in completing the challenge of remaining frozen. This technique also meant more participants successfully calibrated on the first attempt, reducing problems with fatigue and thus were more likely to successfully complete the task with little movement. Second, for those researchers attempting to gather data in public settings, young children may become distracted by the noise or other stimuli around them. One way to overcome this potential challenge is to use noise canceling headphones, which are an inexpensive solution to minimize data loss. Third, a byproduct of using eye-tracking is how to deal with noisy data such as unwanted pupil reactions. Since eye-trackers rely on the pupil to track eye gaze (Hutton, 2019), much of that data collected is based on the pupil's center points. To eliminate the risk of producing noisy data, the eye-tracker should not be set in a room with overly bright or dark lights. The light emitted by stimuli (i.e., computer screens) should also be consistent and not switch between dark and light displays. This might be particularly important for studies examining how much cognitive effort is being applied in a task. In these kinds of studies cognitive effort is typically measured by pupil size, so the researcher will want to ensure that measured pupil changes are not simply explained by changes in light but are in fact explained by the cognitive effort in processing the stimuli.

3. A biological level of analysis of children's spatial reorientation: measuring hippocampal function and structure with trace eyeblink conditioning and MRI

Spatial reorientation, or the ability to orient oneself after being disoriented in space, is by its very nature crucial for human survival. Reorientation supports efficient navigation by allowing individuals to place themselves in the proper spatial location and effectively apply their environmental knowledge to reach a target location (Newcombe, Uttal, & Sauter, 2013). In terms of everyday use, this skill is valuable when faced with navigation tasks, such as being lost on a college campus or driving in a new city. There has been a gradual shift in the literature from showing age-related improvements in reorientation accuracy (Cheng, Huttenlocher, & Newcombe, 2013; Fernandez-Baizan, Arias, & Mendez, 2021), to studying *how* individual differences in spatial reorientation develop. From an RDS perspective, much of the work examining how this ability develops is from a psychological or cultural level of analyses.

From a psychological level of analysis, children's attention to two types of cues guide reorientation success and explain individual differences in performance. Children can pay attention to *geometric cues*, which emphasize the relative length, distance, and angles of environmental objects. They can also pay attention to *featural cues*, such as salient landmarks (Lyons, Huttenlocher, & Ratliff, 2014). Children begin to recognize geometric and featural cues during infancy but do not begin to efficiently use them to reorient until early childhood (Learmonth, Newcombe, & Huttenlocher, 2001; Smith, 2009). Some have proposed that it is the weighting of geometric and featural cues, along with the stimuli's salience, encoded certainty, and perceived usefulness that explain individual differences in spatial reorientation performance (Newcombe & Huttenlocher, 2006). Using a child-friendly reorientation task (Fig. 4; Learmonth et al., 2001), children are placed in a room that provides both geometric and featural cues, and then are asked to search for a hidden object after being disoriented (see Vieites et al., 2020 for more about this task). Children have available to them two types of cues. The color of the walls (red versus white) serves as featural cues. The length of the walls (long versus short) provides the child with geometric information. *Errors* are crucial indicators of the strategies that children use to solve the reorientation task. Children who make diagonal corner errors (i.e., child selects the geometrically equivalent corner from the target object; e.g., corner C instead of corner A) are relying on the geometry of the space to solve the reorientation task, while those who make near corner errors (i.e., child selects an object along the same short wall as the target; e.g., corner B instead of corner A) are drawn to featural cues, using only this information to guide their reorientation. From a cultural level of analysis, the development of individual differences in spatial reorientation ability is a product of the language the child is learning and the environment in which they live (Hermer-Vazquez, Moffet, & Munkholm, 2001; Shusterman & Li, 2016).

We know far less about how individual differences in young children's spatial reorientation ability develops from *a biological level of analysis* (Vieites, Nazareth, Reeb-Sutherland, & Pruden, 2015; Vieites et al., 2020). Data collected from animal models and human adults have provided valuable insight regarding the neurobiological underpinnings of reorientation behavior (for review see Julian et al., 2018). These studies have identified a broad neural substrate supporting spatial reorientation, but converging evidence points to the hippocampus as a vital structure for spatial reorientation. The hippocampus may support spatial reorientation processes by

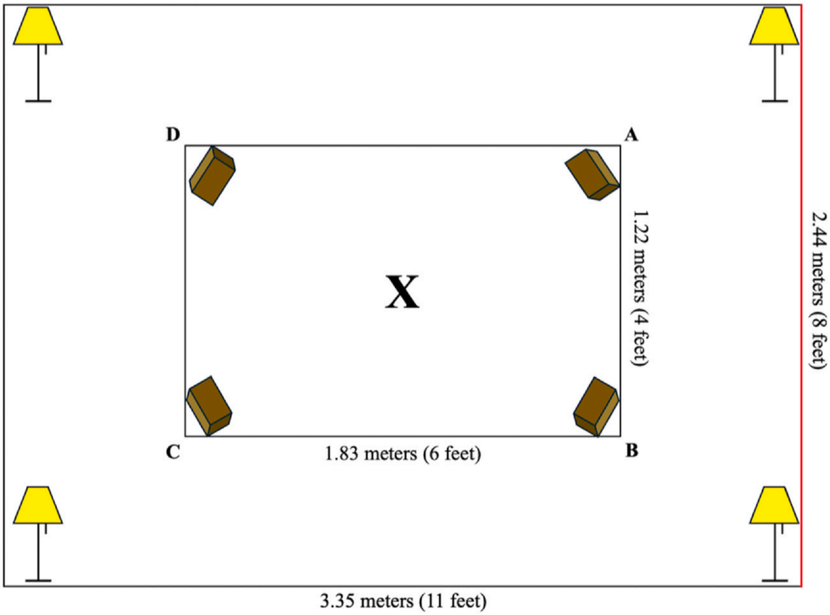

Fig. 4 *Diagram of spatial reorientation task environment. Note.* This task was developed by Learmonth et al., (2001). Children (X) watch as a toy is hidden in location A. All boxes are identical. Children are blindfolded, spun around to disorient, and then asked to find the hidden object. The available cues to solve the task are geometric (length of the walls) and featural cues (color of the walls).

using inputs from sensory systems to generate and maintain internal representations of an individual's external environment, called cognitive maps (O'Keefe & Nadel, 1978; Rolls, 2023). These maps may provide enriched environmental representations to guide reorienting behavior. However, it is unclear what brain regions are involved in young children developing such representations. Below we discuss how we have leveraged both trace eyeblink conditioning and structural MRI technology to study how hippocampal functioning and hippocampal structure may explain individual differences in young children's spatial reorientation ability.

3.1 Trace eyeblink conditioning technology

While functional neuroimaging techniques are commonly used to assess reorientation performance in animal models and adults (Julian et al., 2018), such data are challenging to collect with young children (Poldrack, Paré-Blagoev, & Grant, 2002). Thus, we have been leveraging a trace eyeblink conditioning (EBC) task to evaluate the role of hippocampal functioning in children's spatial reorientation strategy use (Vieites et al., 2020). EBC is a non-invasive device that can elicit an unconditioned response by using conditioning paradigms (Reeb-Sutherland & Fox, 2015). With young children, the unconditioned stimulus is a gentle puff of air into one eye, the conditioned stimulus is a tone, and the conditioned response is a blink. A headset equipped with an air machine and infrared sensor administers the air puff and measures the child's blink responses and latency of the blink in real-time (Fig. 5). In a trace condition, there is a stimulus-free period between the ending of the air puff and the start of the tone (Reeb-Sutherland & Fox, 2015). Trace conditioning is believed to be facilitated by the cerebellum and hippocampus (Reeb-Sutherland & Fox, 2015; Vieites et al., 2015). The EBC paradigm is suitable for use with young children and provides a real-time assessment of children's ability to learn an association between a tone and a puff of air to the eye.

Critically, we have shown that the latency of a blink in the trace EBC paradigm is linked to neurite density in the hippocampus such that those young children who blink closer to the unconditioned stimulus have

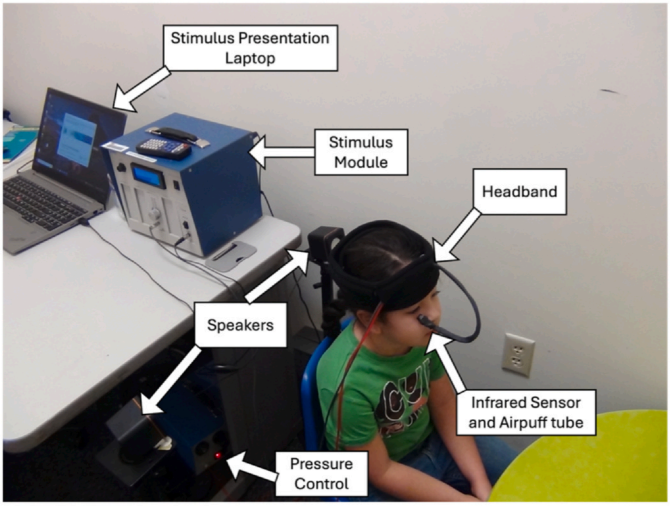

Fig. 5 *EBC task environment. Note*. This non-invasive trace EBC paradigm (San Diego Instruments, San Diego, CA) simply requires the child wear a headband with an infared sensor and airpuff tube over one eye. Children can watch a silent video of their choice while the EBC protocol is administered. In a typical protocol 90 tone-puff trials, 10 tone-alone trials and 10 puff-alone trials are administered to assess associative learning. See Vieites et al. (2015); Vieites et al. (2020); Vieites et al. (2024) for more about this paradigm.

higher neurite density in the hippocampus (Vieites et al., 2024). This research suggests that structural variations in the hippocampus in young children can be accessed via a trace EBC paradigm.

Armed with this technology, we examined whether hippocampal functioning is related to individual differences in young children's spatial reorientation performance (Vieites et al., 2020). We observed a significant relation between children's hippocampal function, as assessed via trace EBC, and their geometric strategy use during the spatial reorientation task, even after controlling for child age. No such relation was found between trace EBC and episodic memory or processing speed performance suggesting a unique role for hippocampal functioning in explaining children's spatial reorientation. Our data nicely align with functional neuroimaging studies in adults, which have associated increased hippocampal activation with geometric reorientation strategies in a virtual environment (Ramanoël et al., 2022).

3.2 Limitations and recommendations for EBC data collection with young children

EBC paradigms are not without their own limitations. For example, EBC cannot pinpoint which subregion of the hippocampus may be driving observed learning (Burman, Starr, & Gewirtz, 2006; Wang, Finnie, Hardt, & Nader, 2012). This may be an important distinction as the anterior and posterior segments of the hippocampus have been implicated in specific cognitive functions (for review see Poppenk, Evensmoen, Moscovitch, & Nadel, 2013). Because we know little about how hippocampal functioning and hippocampal structure explain individual differences in young children's spatial reorientation, we think a valuable complement to EBC data will be neuroimaging data, including structural MRI data.

3.3 Structural MRI technology

One promising technique to complement EBC technology is structural magnetic resonance imaging (MRI). Structural MRI is a non-invasive neuroimaging technique that uses short bursts of radio waves to map cortical tissue, which can detect malformations and compare the structural characteristics of different brain regions (Berger, 2002). In brief, structural MRI uses three different magnetic fields to influence the alignment of hydrogen protons in tissue. A static magnetic field aligns with the protons, a high-frequency alternating field disrupts their alignment, and an alternating pulsed gradient field correlates the MR signals with the proton's original alignment (Plewes & Kucharczyk, 2012). The MR signals are recorded by a computer program which uses the data to generate images. A crucial advantage of structural MRI protocols is their flexibility, as different sequences can be incorporated into a single protocol. T1-, T2-, and diffusion-weighted are three widely used sequences that provide distinct, but complementary neuroanatomical data.

3.4 Structural MRI data

T1-weighted images are created using quick sequences of radio wave pulses and measuring the proton's longitudinal relaxation time, which is the rate at which the affected protons realign with the magnetic field (Plewes & Kucharczyk, 2012). Conversely, a T2-weighted sequence applies a sequence of radio waves with longer intervals to measure transverse relaxation time, which is the time a proton takes to fall out of alignment from neighboring molecules (Plewes & Kucharczyk, 2012). A Fourier transformation is applied to either signal to generate an image. The differing relaxation times for T1- and T2-weighted sequences help highlight different neuroanatomical features. T1 sequences will highlight tissue, making them ideal for evaluating neuroanatomy, while T2 sequences emphasize fluid, which can help visualize pathology (Roberts & Mikulis, 2007). T1 and T2 sequences can also map cortical myelination using the T1w/T2w method outlined by Glasser and Van Essen (2011) and Glasser et al. (2013).

Like T1- and T2-weighted sequences, diffusion-weighted imaging (DWI) also uses radio wave pulses to disrupt proton alignment. However, DWI does not rely on relaxation times; instead, this sequence maps the diffusion of water through the body. When water molecules are in a restricted space, their diffusion becomes orderly rather than random. DWI sequences measure this difference to map structural connections within the brain (Baliyan, Das, Sharma, & Gupta, 2016). DWI compliments the neuroanatomical structure data provided by T1-weighted data by mapping connectivity "fingerprints" between different regions of interest. DWI also has a variety of clinical applications, as irregular diffusion can be an early marker of cortical pathology (Drake-Pérez, Boto, Fitsiori, Lovblad, & Vargas, 2018).

Hippocampal volume, obtained from T1-weighted sequences, is a well-established measure associated with individual differences in various cognitive abilities across the lifespan. From early childhood to adolescence, there is a positive association between individual differences in hippocampal volume and various non-spatial hippocampal-dependent tasks (Botdorf, Canada, & Riggins, 2022). There is also evidence suggesting this relation is consistent with spatial processes. For example, hippocampal volume predicts adolescent performance on mental rotation (Wei, Chen, Dong, & Zhou, 2016), spatial learning (Prathap, Nagel, & Herting, 2021), and spatial memory (Lee et al., 2020) tasks. In adults, hippocampal volume has been associated with age-related declines in navigation and spatial memory accuracy (Konishi, Mckenzie, Etchamendy, Roy, & Bohbot, 2017; Snytte et al., 2022). The incorporation of structural MRI technology can help us expand our examination of individual differences in young children's spatial reorientation from a biological level of analysis. Researchers at the Project on Language and Spatial Development Lab (PLSD) have been working on incorporating MRI and EBC technology to further the neurobiological understanding of spatial reorientation development (Vieites et al., 2024). As mentioned in the *Trace Eyeblink Conditioning Technology* section above, individual differences between hippocampal volume (measured by T1- and diffusion-weighted MRI scans) and neurite density (measured by trace EBC performance) suggest that young children who blink closer to the unconditioned stimulus have higher neurite density in the hippocampus. Ongoing studies at PLSD are now investigating how these neurobiological differences can explain individual differences in spatial reorientation performance.

3.5 Limitations and recommendations for MRI data collection with young children

Structural MRI data can be collected in children as young as neonates with appropriate, study-specific accommodations (for review see Dubois et al., 2021). However, there are practical challenges to collecting usable MRI data from young children. Young children may be fearful of the scanner or have difficulties with lying still for an extended period (Raschle et al., 2012). Given the high cost of maintaining a neuroimaging facility (Rubin, 2017), it is vital to obtain usable data from as many participants as possible. Structural MRI protocols can make participants susceptible to movement during the imaging sequence. These motion artifacts can adversely affect the quality of a scan by creating blurred, distorted images (Van De Walle, Lemahieu, & Achten, 1997).

Given these limitations, Raschle and colleagues (2012) recommend a mock MRI training protocol before the scan to alleviate some of these practical concerns. In a mock protocol, children interact with a replicated version of the MRI machine that will be used for their scan. The mock protocol can help children acclimate to the machine and its sounds.

Additionally, the researcher can use the mock training session to gamify the scan such that children play the "freezing game" where they are encouraged to remain still during the scan (Raschle et al., 2012). Practical considerations can also extend to the scan itself. For example, it may be beneficial for the parent to be in the room and for the MRI facility to provide the child with a movie to watch during the scan (Greene, Black, & Schlaggar, 2016). In addition, taking steps to improve participant comfort, such as providing pillows and blankets, may help reduce motion during the imaging sequence (Vijayakumar, Mills, Alexander-Bloch, Tamnes, & Whittle, 2018).

Collecting structural neuroimaging data also requires specific technological considerations. The MRI coils used for adults may be uncomfortable for children to wear and create unnecessary noise in the data. Tailoring the equipment to the study's target population may provide higher-quality data than using standard devices. For example, Gilbert, Nichols, Gati, and Duerden (2023) found that using an age-appropriate head coil size provides a lower average level of signal noise than a standard adult head coil. Another important consideration is to keep scan times short and employ only necessary sequences. In one study of children between the ages of two and five years, over 70% of children provided a usable scan for one sequence, but only 48% provided viable data for all three sequences (Thieba et al., 2018). When collecting neuroimaging data from young children, scan times of approximately 30 min or less are often associated with high proportions of usable neuroimaging data (Copeland et al., 2021).

There are also important ethical considerations in collecting structural MRI data with young children. In some cases, children may become fearful during the protocol. If this occurs, it is imperative to immediately address this issue and remove the child from the scanner, if necessary. Digital cameras inside the scanner can allow for observation of children's behavior, and microphones can allow researchers to talk directly to participants. Another helpful procedure is to provide children with a button to press or a ball to squeeze if they want out of the scanner. These practices can help ensure that children are safe throughout the imaging protocol. Importantly, these ethical considerations need to be accounted for before the scan begins. Garcini and colleagues (2022) recommend that researchers emphasize reducing barriers to participation in MRI research by devoting time to building trust with communities and families. Recommended practices include providing activities for family members not being scanned and providing caregivers with more thorough explanations of the study's methodology and goals (Garcini et al., 2022). These recommendations are paramount to ensure participant safety and bolster willingness to participate in neuroimaging research.

3.6 Functional MRI technology

In adolescents and adults, functional magnetic resonance imagining (fMRI) can be used to complement structural neuroimaging sequences. While fMRI uses the same technology as its structural counterpart, it leverages magnetic properties to measure neural activity. In brief, increased neural activity is strongly associated with local changes in the balance of oxygenated and deoxygenated blood, which have different magnetic properties that are measured and converted into proxy measures of neural function (Gore, 2003; Logothetis, 2008). However, there are a host of methodological and analytical challenges that limit the viability of using fMRI in young children (Poldrack et al., 2002). Specific recommendations for addressing these issues in developing populations have been reviewed (Barkovich, Li, Desikan, Barkovich, & Xu, 2019; Cusack, McCuaig, & Linke, 2018; Poldrack et al., 2002; Raschle et al., 2012). Although used with older children (Murias, Slone, Tariq, & Iaria, 2019), at this time, fMRI has not been used to study the biological correlates of spatial thinking in young children.

4. A cultural level of analysis of children's spatial language: measuring caregiver spatial language input with ZOOM and LENA technology

Spatial language, talk about size, shape, location, direction and other spatial features of objects and the environment, is often used by both adults and young children when completing a variety of spatial tasks including mental rotation and spatial reorientation. More importantly, it is used in day-to-day tasks such as when giving directions or helping children play with building blocks (Hall et al., 2023). The comprehension and production of spatial words has been linked to better spatial reasoning and better performance on spatial tasks (e.g., Odean et al., 2023; Pruden et al., 2020). For these reasons, it is important to understand how individual differences in young children's spatial language develops. To study this, we have taken a cultural level of analysis, given the abundance of evidence to suggest that the environment and the culture in which children live shapes their spatial language development.

From a cultural lens, we have learned that individual differences in spatial language may develop differently across languages (Pruden & Odean, 2017) and can depend on parent-child interactions (Hall et al., 2023; Pruden & Levine, 2017). Cross-cultural evidence suggests that children use different words to encode spatial relations depending on the reference frame of their native language. For example, Haun and Rapold (2009) found that children who speak an egocentric (person-centered) language encode a series of turns as left and right, while those who speak an allocentric (object-centered) language encode the same turns as north and south. The non-verbal representation of the spatial concept is consistent across egocentric and allocentric languages; the critical difference is the spatial terms linked to the spatial representations.

The effects of cross-cultural language differences can be observed early in development. Infants as young as seven months can attend to and discriminate changes in objects' motion (Pulverman, Song, Hirsh-Pasek, Pruden, & Golinkoff, 2013), but children begin to talk about motion in language-specific patterns by 24 months (Choi & Bowerman, 1991). These cross-linguistic differences may involve syntactic variability in the languages children are exposed to. For example, motion is generally conveyed with verbs in English and adverbs in Spanish (Talmy, 1991), which may in turn direct children's attention toward different aspects of their spatial environment (Pruden & Odean, 2017). This may likely lead to different patterns of spatial language use in children learning different languages.

There is also ample evidence that spatial language exposure bolsters young children's spatial development, regardless of their native language. For example, block play has been found to elicit spatial language production in native Chinese- and English-speaking children (Ferrara, Hirsh-Pasek, Newcombe, Golinkoff, & Lam, 2011; Yang & Pan, 2021). In English-speaking children, longitudinal data suggest that individual differences in spatial language production predicts superior spatial skills later in development (Pruden et al., 2011). Cross-cultural data indicate that language has the capacity to aid spatial development irrespective of the speaker and listeners' native language. For instance, demonstratives, words that direct attention (e.g., *that*, *this*), are found in 150 different languages across the world and represent unique forms of parent-child interactions (Diessel & Coventry, 2020). Studies that focus on children's sociocultural environment may often record parent-child interactions during a structured play or free play session (e.g., Hall et al., 2023). For example, Lee and Wood (2021) examined parent-child interactions in the home setting and found that play behaviors during these interactions (e.g., encouragement and teaching) are linked to the development of spatial skills in young children.

From an RDS perspective, it is imperative to characterize how these interactions vary across linguistic, social, and cultural contexts (Pruden & Odean, 2017). Modern technology may make collecting these data easier by bringing researchers into homes via Zoom (e.g., Garcia-Sanchez, Dick, Hayes, & Pruden, 2024) or by automating the language collection process via the use of LENA technology (Odean, Nazareth, & Pruden, 2015).

4.1 Zoom as a platform for spatial language data collection

Zoom Video Communications Inc. (n.d.) or Zoom is a video communications platform that makes communicating via video easy and accessible. Zoom can be downloaded to any computer, laptop, tablet, or other smart device, making it easier to communicate regardless of location. It also offers a variety of features like a chat option, emoji reactions, and breakout rooms to help users interact and enhance the online communication platform. The use of Zoom for online data collection has gained popularity in recent years, particularly during the COVID-19 pandemic (Boland et al., 2022). It is an effective platform to collect a larger amount of data more quickly than traditional in-person studies (Boland et al., 2022; Gray, Wong-Wylie, Rempel, & Cook, 2020).

Zoom is a powerful tool for collecting young children's behavioral data and recording parent-child interaction data. It not only increases one's ability to recruit a large number of participants, yielding larger sample sizes, but also expands one's ability to recruit participants across diverse demographic backgrounds. Its ability to expand participation to include individuals beyond the typical white, educated, industrialized, rich, and democratic (WEIRD) samples is a path to increasing diversity in developmental research.

Investigating how spatial language develops within a child's environment often requires researchers to visit homes or have families visit a lab setting. This may not always be possible and often difficult to get families to agree to such things. However, using Zoom has made this easier by bringing researchers into homes (Garcia-Sanchez et al., 2024). Using the recorded videos of Zoom can make coding parent-child interactions in a natural setting more accessible.

4.2 Zoom data

Zoom can provide multiple types of video data that can later be used for analysis and coding. Depending on the recording setting, Zoom videos can be presented with gallery view (video of both the parent-child dyad and the experimenter), speaker view (video of only the parent-child dyads) or audio only. Zoom also provides automatic video transcriptions, which can be used for calculating total or specific language uses (e.g., Hall et al., 2023; Pruden & Levine, 2017). For example, Hall and colleagues (2023) coded parent prosocial talk and spatial language during a free play session to study how they related to children's spatial language production. Both types of speech were found to predict a greater quantity of child spatial language use. Video quality and sound quality should be checked and adjusted to optimal before Zoom recording.

4.3 Zoom advantages

Zoom recordings may encourage more authentic behaviors by increasing participant comfort as participants select the context in which they participate (e.g., home), compared to laboratory visits that some argue do not approximate natural parent-child interaction. Unlike lab visits where the setting is controlled across participants, home settings vary tremendously across participants. Clear instructions and directions about how the dyads are expected to set up their home environment must be given before the online session to ensure smooth data collection and high-quality data.

4.4 Zoom and other open-source software for mental rotation and spatial scaling data collection

To deliver spatial tasks via Zoom, researchers need to set up the tasks in programming tools. This can be done by incorporating other software platforms. An increasing number of open source software platforms have been developed for the administration of online experiments and tasks, including Gorilla (https://gorilla.sc/) and Psychopy (https://psychopy.org/).

For example, the *Picture Rotation Task* (*PRT*; Quasier-Pohl, 2003) and the *Spatial Scaling Task* (*SST*; Frick & Newcombe, 2012) have recently been adapted for use in Zoom. This made examining the role of intergenerational transmission of spatial ability between mother and child easier for Garcia-Sanchez et al. (2024). Mother-child engagement in spatial activities in the home and mother toy choices for the child indirectly explain relations between mother and child spatial ability (Garcia-Sanchez et al., 2024).

In our ongoing work we have adapted the *Children's Mental Transformation Task* (*CMTT*; Levine et al., 1999), along with the adapted *SST,* for use on the Zoom platform to examine relations between individual differences in children's attention to social and non-social events, and their spatial abilities as part of a larger, multisite study on the development of attention and multisensory skills (NIH Multisensory Data Network Study;

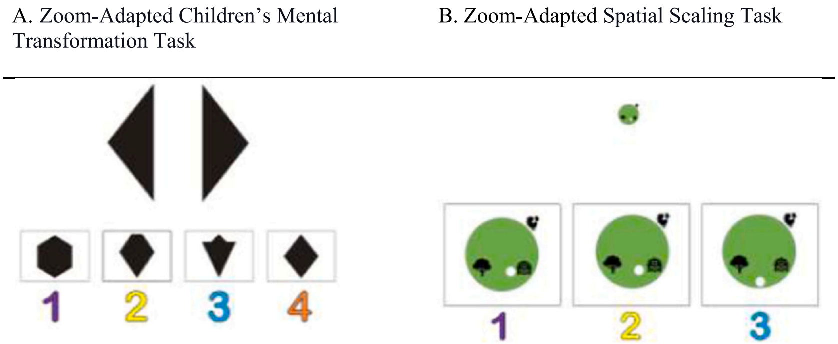

Fig. 6 *Zoom-Adapted Spatial Tasks. Note.* Item A is an example from the Adapted Children's Mental Transformation Task. Participants are asked to determine which of the four shapes at the bottom make the two pieces on top. Item B is an example of the Adapted Spatial Scaling Task. Participants are asked to point which of the three maps on the bottom matches the one on top.

https://sites.google.com/view/fiumultinet/wiki-homepage). Using Gorilla as the task builder to easily display the trials on Zoom, an experimenter can start the task on their computer and then share their screen with participants for data collection. The CMTT is a 2-D mental transformation task, where participants see two pieces and four shapes on a screen. They are asked to indicate which shape the two pieces make. Participants can respond with the number under each shape to indicate their answer (see Fig. 6A). There is one practice trial and 32 test trials in the task. The number of accurate responses is recorded by the program and percent correct can be used as the main variable of interest. The SST assesses the ability to successfully map the distance between different sized locations. A target map and three same-sized maps are presented on the computer screen. The target map is scaled to a smaller size (1/4 of the size) than the three maps. Only one of the three larger maps is the same as the target map (see Fig. 6B). Participants are asked to respond with the labeled number to indicate which of the larger maps matches the target map. There are two practice trials and 10 test trials in the task. The number of correct responses is recorded, and percent correct can be used as the main variable of interest.

4.5 Zoom limitations and recommendations

Zoom technology is not without its limitations. Low bandwidth or wi-fi connectivity issues can prevent high-quality video recordings, which in turn can result in frequent video lags and poor transcription quality. Poor video quality can impact how quickly a researcher can transcribe a video making the data analysis process longer. We suggest having several research assistants trained to transcribe to expedite data analysis and ensure high reliability of transcriptions. In cases, where videos and their accompanying audio are not of the highest quality, we recommend avoiding the use of automated transcription programs in lieu of manual transcription of the video.

Another limitation is that Zoom requires access to both the internet, and either a computer or a smartphone. If there is a lack of access to computers or smartphones this may prevent people from participating, particularly those from low resource homes. If your study allows it, we recommend having tasks that can easily be completed over a smartphone instead of a computer, as smartphones are more widely accessible than computers even by those from low resource homes. To adapt a task for use on a smartphone may require limiting interactions with the device (e.g., moving a mouse) and having more tasks that require verbal responses. This can be problematic however with young children. Finally, we see that sometimes, even with access to computers or smartphones, the knowledge or confidence of correctly using Zoom may also impact participation. Therefore, we recommend sending written and video instructions prior to the study session to allow participants to practice using Zoom.

Researchers should also be mindful of the possibility of participant scams over Zoom. While thankfully rare, participant scams can include providing false demographic information to be eligible to participate (e.g., we have had personal experience in families signing up to only have no child present for testing on Zoom). The majority of these participants who do not meet eligibility criteria are best identified during the recruitment process, if possible, but at worse can be detected during the data collection process when the participant is visible during Zoom conferencing. Scams can compromise the completion of a study, considering the time and efforts researchers put into recruitment and data collection. Unresolved data from "fake" participants may lead to biased data and unreliable findings (Teitcher et al., 2015). We suggest having a procedure or script ready to notify the participant that testing will not continue, and compensation will not be provided if they do not meet the participation requirements. Alternative considerations are to use recruitment platforms that screen families for eligibility (e.g., https://childrenhelpingscience.com; https://scistarter.org), but there is usually a cost to these platforms either in terms of cost or the inability to data share.

4.6 LENA technology

One technology that can be improved and leveraged to measure spatial language for future research is LENA (Language ENvironment Analysis; Xu, Richards, & Gilkerson, 2014). This technology uses a small wearable Digital Language Processor (DLP) device that can be worn in virtually any environment such as the home, school, or museum setting and can record up to 16 continuous hours of language interaction. LENA measures and automatically produces data visualizations of daily and hourly quantity of adult and child vocalizations produced, conversational turns, and the complexity and duration of children's speech. Although LENA was originally designed to capture these aspects of domain-general language production, transcripts can currently be produced to allow for analyses of domain-specific spatial language. However, to date, no published studies have explicitly used the LENA device to record and measure domain-specific spatial language. Although He et al. (2022) mentioned that LENA was used to record the audio data in an efficacy study of a language input curriculum with 37 caregiver-child dyads, the authors stated that they also video-recorded interactions and used these video recordings to code for spatial language use. There is still much to be done to leverage LENA technology for use in examining how children's spatial language develops.

4.7 LENA limitations and recommendation

Researchers should be aware of the limitations of LENA technology. LENA technology cannot identify tokens, types, or counts for spatial specific and other domain-specific language use (Odean et al., 2015). We recommend having a team of transcribers trained in identifying and coding for specific language use. There are also challenges to collecting audio data in louder environments such as classrooms or museums. Researchers gathering data in noisy environments or with multiple speakers may want to consider the use of additional data checks to ensure the software is providing proper automated counts for the speaker of interest.

5. Envisioning the future of the study of individual differences in young children's spatial thinking: can we leverage artificial intelligence?

Artificial intelligence (AI) is a computer science discipline that focuses on the development of intelligent machines that are capable of learning (McCarthy et al., 2006). AI has been an increasingly common tool for psychological research. AI has been used to reduce the amount of time spent collecting data (Park et al., 2023) and assessing data quality. Recruitment efforts may also be facilitated using AI, as many organizations are beginning to incorporate AI as a way to identify and select talent (Hahne & Petta, 2024). Below we consider potential uses for AI using the RDS perspective to guide our discussion.

5.1 Artificial intelligence uses from a psychological level of analysis

AI may serve as a platform for measuring complex constructs like human cognition. AI demonstrates promise for improving the effectiveness in cognitive testing in three areas: behavioral sensing, data mining, and cognitive modeling (Kunda, 2019). Cognitive testing used in conjunction with AI is likely to aid in the quantification of individual test-taking behaviors (behavioral sensing), identification and extraction of meaningful patterns from behavioral datasets (data mining), and mapping of observed behaviors onto hypothesized cognitive strategies (cognitive modeling). This can be particularly helpful when using eye-tracking data to measure a cognitive process. Eye-tracking devices rely on patterns of eye movement detection that are typically assisted by different AI tools, such as machine learning algorithms (Kędras & Sobecki, 2023). Combining eye-tracking with AI technology allows for detailed eye movement recognition systems to assess how individuals, particularly children, solve spatial tasks with little to no human interference or biases (i.e., human researchers usually determined AOI's). With AI, we may be able to quickly identify and classify a child's cognitive strategy for solving a task with minimal test trials, reducing the need for young participants to provide lots of data.

5.2 Artificial intelligence uses from a biological level of analysis

The breakthrough of AI has created new opportunities for improving the quality and efficiency of medical devices used in various scientific fields. In recent years, AI has been used to alleviate several practical issues with MRI data collection, such as using deep-learning techniques that can reduce scan times and remove motion artifacts (Shimron & Perlman, 2023). AI has also helped with issues in eye-blink detection occurring in real-time, something that has been particularly important to those suffering from Amyotrophic Lateral Sclerosis (ALS). Many late-stage ALS patients rely on eye-blink detection software to communicate their needs with their caregivers. AI has facilitated face detection, face alignment, region-of-interest extraction, and eye-state classification in patients with ALS (Medeiros et al., 2022). These kinds of uses for AI are quite promising to our own work with eye-tracking and eye-blink conditioning, as we would be able to use AI to classify eye-gaze and eye-blink data. These techniques also handle large data sets, which are quite common in both eye-tracking and eye-blink conditioning data. AI can expedite the handling of "big data" by producing models that quantify the information.

5.3 Artificial intelligence uses from a cultural level of analysis

A key benefit of LENA is that it can be used to easily capture large-scale, naturalistic language data in a variety of languages and dialects. However, spatial language is currently manually coded by human coders. Technology that we have leveraged for coding spatial language from videos has included Zoom or Datavyu (https://datavyu.org) and allow for human coders to add information about the socio-cultural context. Currently, LENA software does not specifically identify domain-specific words like spatial words or other types of words. There is opportunity here for AI technology to be leveraged with LENA software to enhance this software's capabilities to identify specific types of words and provide automated counts of these types of words. That is, LENA could be integrated with AI algorithms capable of recognizing and analyzing spatial language within recorded audio or transcripts.

6. Other future directions

As we had outlined previously, we are operating from a Relational Developmental Systems (RDS) perspective and argued that development is best explained by the co-acting of multiple systems (e.g., cognitive strategies, hippocampal functioning and structure and caregiver spatial language input) operating at various levels of analyses (i.e., the psychological, biological, and cultural) over time to produce individual differences in young children's spatial thinking. Most of our previous research, and others' too, has focused on the examination from one level of analysis or addressing the role of one system. Yet, to fully understand the complexity of development of spatial thinking we will need to examine multiple systems together or from different levels of analysis in the same study.

In a recent study by Casasola, Wei, Suh, Donskoy, and Ransom (2020) the effects of spatial language during playtime on spatial skills were evaluated. They found that the quantity and diversity of adult spatial language (a system from a cultural level of analysis) was strongly associated with children's post play mental rotation performance. However, there is more to say about what affects the child's spatial skills, including proposed systems from the psychological (i.e., cognitive strategies) or biological (hippocampal volume) levels of analysis. Ideally, a single study would be able to analyze spatial thinking across all three levels of analysis. We understand that this is not always possible for many reasons such as funding considerations, time, and limited equipment. In the sections below we examine how the devices discussed above can be used together to attempt to investigate spatial thinking from multiple RDS levels and across different systems.

6.1 Future study ideas with eye-tracking technology

Eye-tracking studies can be used to measure other cognitive abilities beyond mental rotation. For instance, with wearable eye-trackers researchers can track the path a participant takes during a spatial reorientation task. While the path an individual takes in being recorded, heatmaps can indicate what artifacts or landmarks are most often looked at. This information can be interpreted to determine if allocentric or egocentric navigation is being used to measure spatial reorientation at the cognitive level and even the social level.

6.2 Future study idea with eye-tracking and Zoom technology

Eye-tracking technology can be incorporated with other technology such as Zoom. This is useful for two reasons. First, as mentioned before, using Zoom makes evaluating spatial thinking from a social perspective easier. Second, some eye-tracking software can work with webcams making the possibility of measuring spatial skills at the psychological level of analysis more attainable (Wisiecka et al., 2022). However, webcam eye-trackers still need improvements in their accuracy and precision as many do not report data on these important variables. When webcam eye-trackers become more advanced this would be a great approach to collecting a variety of data faster and reaching a diverse population.

6.3 Future study idea with MRI and eyeblink conditioning technology

More work is needed to investigate spatial thinking from the biological level of analysis. In our own lab, we have been using both trace EBC to measure hippocampal functioning and structural MRI data to measure hippocampal volume, as well as studying systems like working memory (from a psychological level of analysis) to see if these systems together explain individual differences in 4- to 6-year-olds' spatial thinking. We still have much to do as few studies examining the mechanisms explaining individual differences in spatial thinking gather neurobiology data. It will be challenging to develop systems-level models of spatial development without first increasing the amount of neurobiology data available.

6.4 Future study ideas with LENA technology and artificial intelligence

Future work should attempt to successfully train Naïve Bayes algorithms to classify language from transcripts as "spatial" or "non-spatial" as a first step to more advanced automatic coding of spatial language. This could be developed for finer-grained categorical identification (e.g., categorizing "rotate" as a spatial orientation/transformation word, "curve" as a spatial feature/property word, or "cube" as a 3-dimensional shape word) and integrated with LENA's existing transcription capabilities to automatically identify and tag spatial language expressions in the generated transcripts. This would allow for researchers to locate spatial language quickly and reliably for further analyses without the need for extensive human involvement. Although LENA technology is currently limited in its efficiency and efficacy for coding and analyzing domain-specific lexicons, such as spatial language (e.g., Odean et al., 2015), we think advances in AI may be leveraged to overcome challenges in identifying domain-specific language use and then calculating its use via its automated software like LENA.

7. Conclusion

In the current paper we have outlined five technological tools that can be leveraged to measure spatial thinking in young children. Operating from a Relational Developmental Systems perspective, we discussed the development of individual differences in young children's mental rotation, spatial reorientation, and spatial language from the psychological, biological, and cultural levels of analyses. Our goal was to inspire the use of these tools to examine how individual differences in young children's spatial thinking develops by providing details on how these tools have been used and the type of data they provide, and how limitations in working with these tools can be overcome. We believe that approaching the development of spatial thinking from a rich theoretical perspective along with leveraging innovative technology will finally allow us to answer *how* young children develop.

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