The Role of Motor Skills in the Development of Mental Rotation Abilities from Infancy to Preschool Age

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Declaration

The work presented in this dissertation has been carried out by me under the guidance of Prof. Dr. Gudrun Schwarzer and Prof. Dr. Bianca Jovanovic at the Justus Liebig University Giessen, Germany.

“I hereby declare that I have prepared the dissertation at hand independently and without undue aid or the use of any resources other than those indicated within the dissertation. All parts of my dissertation taken either verbatim or analogously from the published or unpublished works of or based on oral communications with others are indicated as such. Regarding all aspects of my scientific enquiries as they appear in my dissertation, I have upheld the tenets of good scientific practice as laid out in the "Satzung der Justus-Liebig-Universität Gießen zur Sicherung guter wissenschaftlicher Praxis" and complied with the precept of ethics, data protection and animal welfare. I declare that I have neither directly nor indirectly given monetary or any other valuable consideration to others in connection with the dissertation at hand. I declare that I have not presented the dissertation at hand, either in an identical or similar form, to an examination office or agency in Germany or any other country as part of any examination or degree. All materials from other sources, as well as all works performed by others used or directly referenced within the dissertation at hand, have been indicated as such. In particular, all persons involved directly or indirectly in the development of the dissertation at hand have been named. I agree with the screening of my dissertation for plagiarism via offline or online detection software.”

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Dedicated to my loving Amma and Appa,

Abstract

From the earliest months of life, infants are captivated by objects, exploring them from multiple perspectives, grasping toys, chasing rolling balls, and anticipating their paths (Örnkloo & von Hofsten, 2007). These behaviours illustrate the emergence of visuospatial understanding and the formation of mental representations of objects and their movement. A foundational visuospatial process underlying these abilities is mental rotation (MR), defined as the capacity to mentally transform and manipulate objects in space (Linn & Petersen, 1985). Given MR's pervasive role in everyday activities and its predictive power for mathematical thinking and later academic success (Wai et al., 2009), understanding its developmental course is both scientifically significant and practically valuable.

Despite MR's importance, the development trajectory of three-dimensional mental rotation (3D-MR) remains poorly understood. While cross-sectional studies demonstrate the emergence of 3D-MR in infants (Johnson & Moore, 2020) and its further development in preschoolers (Frick et al., 2013a), longitudinal investigations tracing its continuity across these two early stages are scarce. This gap is particularly surprising as the preschool years are a critical period for preparing children for formal schooling. Although infant studies highlight close links between motor development and 3D-MR (Schwarzer et al., 2013b), it remains unclear whether these early motor experiences (such as self-produced locomotion) have lasting predictive relations with 3D-MR into the preschool years. Additionally, it remains unclear whether concurrent links between motor skills and 3D-MR are also present in preschool children. Moreover, visuospatial processing encompasses intra-object processing (such as MR) and inter-object processing (such as prediction of object trajectories), both relying on the construction and transformation of spatial representations (Newcombe et al., 2013). Yet these two processes have been studied in isolation, leaving their developmental interrelations unexamined.

This dissertation provides a comprehensive investigation of 3D-MR development from infancy (9 months) to preschool ages (4-6 years), integrating longitudinal and cross-sectional approaches across three empirical studies employing age- appropriate yet conceptually comparable 3D-MR tasks. Study 1 examined the longitudinal developmental trajectory of 3D-MR from infancy to preschool age (using screen-based tasks) and investigated the role of early motor experience. Results revealed infants who demonstrated stronger 3D-MR performance at 9 months of age, particularly those who had acquired crawling ability, also showed better 3D-MR performance at 4 to 6 years of age, providing potentially the first evidence for a longitudinal link between 3D-MR abilities across these developmental stages and highlighting the long-term relevance of early self-produced locomotion. Study 2 explored the relationship between motor skills and 3D-MR (employing a novel block-based 3D-MR task) during the preschool

years using a cross-sectional design. The study revealed a developmentally nuanced pattern: associations between 3D-MR and gross motor skills were observed in younger preschoolers (4.6–5.5 years), whereas associations with fine motor skills emerged only in older preschoolers (5.6–6.5 years). These findings suggest a developmental shift in the motor foundations supporting spatial transformation abilities during early childhood. Study 3, explored the relationship between intra-object and inter-object processing during infancy. Although no direct association between prediction ability and 3D-MR was observed, likely reflecting differences in task demands and representational requirements, self-produced locomotion was associated with infants' visual prediction abilities. This finding converges with Study 1 and highlights the potential role of locomotor experience in early visuospatial development, while opening avenues for future research.

Beyond its empirical contributions, this dissertation makes a significant methodological advance by developing age-appropriate and conceptually comparable 3D-MR tasks that can be used across infancy and preschool age. Notably, these tasks are one of the first 3D-MR paradigms, to demonstrate reliable angular disparity effects in preschool-aged children using both screen-based and tangible stimuli.

Taken together, these findings provide a developmentally grounded account of 3D-MR in early years of life. By demonstrating longitudinal continuity in 3D-MR, enduring links with self-produced locomotion, motor proficiency, and interplay of perception and action, the present work offers compelling support for embodied theories of spatial cognition. Beyond advancing theoretical understanding, these findings have important implications for educational practice and early intervention. Given the well-established links between MR, STEM achievement, and broader academic success (Uttal et al., 2013), clarifying the perceptual-motor foundations of spatial thinking may inform developmentally sensitive strategies and targeted interventions to support spatial skill development, particularly for children at risk of delay, thereby promoting more equitable educational outcomes.

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List of Abbreviations

2D	Two-dimensional
2D-MR	Two-dimensional Mental Rotation
3D	Three-dimensional
3D-MR	Three-dimensional Mental Rotation
ANCOVA	Analysis of Covariance
ANOVA	Analysis of Variance
BiRT	Bilder Rotations Test
CMTT	Children's Mental Transformation Task
CPM	Coloured Progressive Matrices
LoMo 3-6	Leistungsinventar zur Objektiven Überprüfung der Motorik von 3- bis 6-Jährigen
MOT 4-6	Motoriktest für vier- bis sechsjährige Kinder
MR	Mental Rotation
PR	Prediction Rate
PRT	Picture Rotation Task
RT	Reaction time
STEM	Science, Technology, Engineering, and Mathematics
T1	Test Point 1
T2	Test Point 2
VoE	Violation-of-Expectation
VSTM	Visual Short Term Memory

“The true mark of intelligence is not knowledge but imagination.”

— *Albert Einstein*

Chapter 1

Introduction

Imagine a scenario: a 9-month-old watches a rattle tumble down from the caregiver's hand. Instead of dropping straight down, it spins and lands at an awkward angle on the floor. The infant crawls forward, visually tracks the new orientation, and then reaches by rotating their wrist mid-movement to align their hand with the handle. This tiny gesture exemplifies the early signs of mental rotation ability. Mental rotation (MR) is a fundamental spatial skill that enables humans to imagine and visualise how two-dimensional (2D) and three-dimensional (3D) objects appear from different perspectives and orientations (Linn & Petersen, 1985; Shepard & Metzler, 1971). Long before humans can solve puzzles or read maps, infants are already simulating how 3D objects might look and feel from different orientations, using these internal representations to guide their actions (Schwarzer & Jovanovic, 2024). What begins with picking up a rattle from the floor, over the course of childhood, develops into the capacity to imagine entire scenes and use symbolic representations, such as diagrams, flowcharts, or spatial metaphors, to solve abstract problems (Goel & Dolan, 2003; Hegarty, 2004; Knauff, 2007). The development of MR, however, does not occur in isolation. It unfolds in close coordination with emerging motor abilities such as reaching, grasping, and especially crawling, which expands infants' engagement with the spatial environment, affording opportunities to perceive and act upon objects from multiple perspectives (Ravid-Roth et al., 2025; Von Hofsten, 2004). Through these actions, infants integrate visual, proprioceptive, and tactile feedback, progressively building links between bodily movement and the spatial properties of objects (Jovanovic et al., 2008; Preißler et al., 2021; Schwarzer, 2014). Understanding how MR develops from infancy through the preschool years, and the extent to which motor development contributes to this process, is the central question motivating this dissertation.

Beyond everyday functioning, MR is a strong predictor of academic achievement and plays a foundational role in science, technology, engineering, and mathematics (STEM) learning (Wai et al., 2009). Being a central component of spatial reasoning throughout childhood, MR supports a wide range of problem-solving tasks in technical and medical contexts (Kell et al., 2013; Miura et al., 2019). Additionally, it contributes to early perceptual learning, such as discriminating similar letters like p, d, b, and q during reading acquisition (Corballis & McLaren, 1984; Da Resque et al., 2023). Studying the development of MR is therefore essential for understanding how children acquire the spatial skills that support both cognitive growth and school readiness. The preschool years, in particular, represent a crucial period for spatial development and are increasingly targeted in educational research and practice. Insights into MR development can inform the design of evidence-based learning materials, spatially enriched play, and classroom interventions aimed at enhancing academic outcomes (Piri & Cagiltay, 2024). In a society driven by technological advancement, understanding its developmental progression and role throughout the lifespan can reveal various aspects of spatial representation and help develop standardised programmes and curricula to improve academic outcomes. Moreover, in clinical populations or children with slower learning speeds, targeting this skill could have a greater impact by enabling them to design more specialised intervention strategies (Campos et al., 2009; Yildiz et al., 2024).

Despite the growing recognition of spatial cognition as an essential developmental domain, most recent research has focused on the MR of 2D objects, such as flat shapes or figures presented on screens. However, real-world interactions rarely occur in two dimensions. Everyday actions, such as grasping a cup, building blocks, or navigating a play environment, require the ability to mentally represent 3D objects in space. Compared to two-dimensional mental rotation (2D-MR) tasks, three dimensional mental rotation (3D-MR) demands a deeper understanding of object depth, volume, and orientation in relation to the observer, making it a more cognitively demanding measure of spatial ability (Johnson et al., 2012; Soska & Johnson, 2013).

According to Newcombe et al. (2013), spatial representation of objects encompasses two broad processes. Firstly, intra-object processing, which involves mental manipulation of objects, as seen in MR. And secondly, inter-object processing, which involves anticipating object locations and their relationships. Integration of these processes, along with environmental cues, helps constitute, plan and execute goal-directed actions (Kubicek & Schwarzer, 2018). For instance, when a toy car moves under a sofa, it is temporarily occluded. However, the infant can still anticipate the toy car's orientation and location from the other end of the sofa. It could be that prediction ability, such as anticipating an object's future location or orientation, may allow infants to simulate rotations mentally before acting. Understanding the development of these skills and how they both relate to each other provides a window into the processes underpinning complex reasoning and problem-solving later in life.

Additionally, motor skills are a facet that develops in tandem and tends to support the development of spatial skills. Motor experience has been proposed as a critical factor supporting MR development (Adolph & Franchak, 2017; Frick et al., 2014).

Increasing evidence suggests that motor abilities, especially self-produced locomotion and manual exploration, play a crucial role in shaping spatial cognition from early on. Through these motor actions, infants gain new perspectives and opportunities to interact with their surroundings, experiences that appear to support the formation of internal spatial representations (Von Hofsten, 2004). This coupling between motor and cognitive development has long been recognised in developmental theory and practice. Many standardised developmental assessments, such as the Bayley Scales of Infant Development (Bayley, 2005; Michalec, 2011), implicitly reflect this connection: cognitive performance in infancy is often inferred from tasks that require motor responses. Theoretically, this link was most prominently articulated by Piaget and Cook (1954), who proposed that knowledge emerges from infants' sensorimotor interactions with the environment, and action is the foundation of thought. Similarly, Gibson and Pick (2000) argued that perceptual development depends on motor abilities, as movement expands infants' understanding of affordances and spatial layouts. As motor skills advance, so too does the child's perception of how they can act upon and influence their environment. However, studies examining whether these early motor experiences contribute to MR across developmental time points remain scarce. Most of the recent literature focuses on infancy or preschool age cross-sectionally, leaving a significant gap in our understanding of the development of 3D-MR across these formative years and the role of motor skills in 3D-MR development.

The overarching goal of this dissertation is to advance the understanding of 3D-MR development from infancy through preschool years. By applying both cross-sectional and longitudinal approaches, this dissertation elucidates the potential role of motor skills in the development of 3D-MR across both these early stages of life and explores how infant 3D-MR relates to 3D-MR performance at preschool age. A key methodological objective of this dissertation is the development of age-appropriate and conceptually comparable tasks that allow assessment of 3D-MR across both ages, thereby enabling longitudinal comparisons. The central assumption is that motor skills, including self-produced locomotion in infancy as well as fine and gross motor abilities in the preschool period, constitute important factors that support 3D-MR development. Furthermore, by examining whether predictive processing abilities are associated with 3D-MR in infancy, this research aims to deepen the understanding of the link between inter-object and intra-object processing.

This chapter provides a comprehensive overview of the theoretical framework underpinning the present dissertation. It begins by reviewing relevant theoretical perspectives and empirical findings of spatial skills (Section 1.1), followed by a detailed examination of MR research conducted during infancy (Section 1.2) and the preschool years (Section 1.3), reflecting its development across both stages. Drawing on the existing literature, Section 1.4 identifies key research gaps in state-of-the-art knowledge that motivate the present research. Section 1.5 subsequently outlines the primary research aims and objectives of the dissertation.

Chapter 2 presents, one of the first longitudinal study examining the developmental trajectory of 3D-MR from infancy through preschool years, with particular emphasis on the contribution of motor skill development. Chapter 3 reports findings from the second study, focusing on preschool-aged children and investigating the associations between 3D-MR abilities and both fine and gross motor skills. Chapter 4 describes a pilot study that explores the relationship between intra-object and inter-object processing, providing preliminary insights into underlying cognitive mechanisms. Chapter 5 offers an integrative general discussion that synthesises results across all studies (reported in Chapter 2-4) and discusses their future theoretical and developmental implications and limitations. Finally, Chapter 6 presents the overall conclusions of the dissertation.

1.1 Foundations of Spatial Skills and Motor Development

1.1.1 Conceptualising Spatial Skills

Spatial ability is the capacity to represent the position, form, interrelations, and movement of objects (Newcombe & Frick, 2010), has long been regarded as partly independent from general intelligence, verbal, and reasoning skills (Rimfeld et al., 2017). As they are vital for guiding action and interaction with the environment, they are critical for adaptive functioning across species. Turtle hatchlings orient toward the sea, food-caching birds locate hundreds of stored seeds, and humans navigate their homes, communities, and even novel environments using spatial cues to achieve goals (Kaltner & Jansen, 2017). These basic behaviours across species underscore that evolutionary pressures likely shaped our cognitive architecture, providing the foundation for the emergence of spatial skills (Poucet, 1993). While evolutionary perspectives highlight why spatial skills are adaptive, developmental psychology seeks to explain how and when these capacities emerge and mature in humans, beginning in infancy. Development of spatial skills is shaped by both biological maturation, particularly in parietal and frontal brain regions, and environmental influences such as play, education, and cultural tools (Gold et al., 2023).

1.1.2 Typology of Spatial Skills

Beyond being separable from other cognitive domains, spatial thinking itself is often described as multidimensional, comprising several interrelated but distinct components. A model developed by Uttal et al. (2013), which is rooted in cognitive neuroscience and provides a top-down conceptualisation of spatial skills, elaborates on the typology of spatial skills. This framework distinguishes between intrinsic and extrinsic abilities and further classifies each as either static or dynamic. Intrinsic skills involve reasoning about within-object spatial relations, such as the size, orientation, and configuration of an object and its parts, whereas extrinsic skills involve between-object relations, including relationships between objects and their spatial frames of reference. Dynamic skills involve transformations or movements, such as MR or folding, while static skills involve the representation of spatial information without transformation.

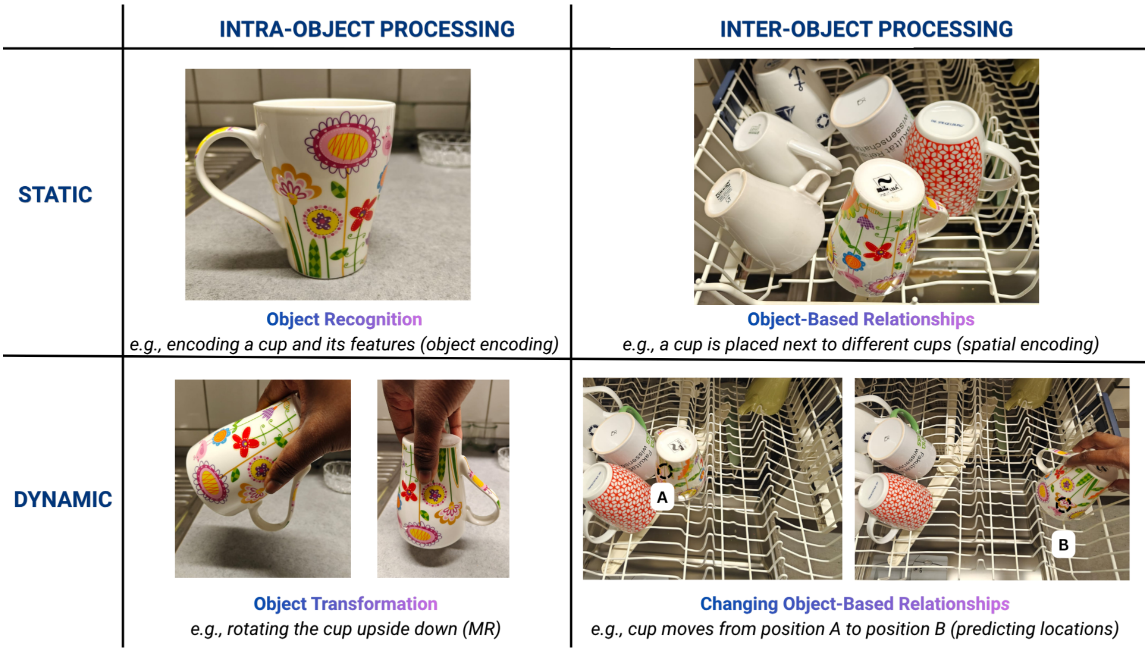

Figure 1.1: Example of intra-object and inter-object processing. Based on Newcombe et al.'s (2013) classification, an original example of loading a cup in a dishwasher is depicted to distinguish the two processes across static and dynamic classifications. Figure style adapted from (Newcombe, 2018)

Building on this framework, Newcombe et al. (2013) proposed that the intrinsic–extrinsic distinction can also be conceptualized in terms of intra-object versus inter-object processing, suggesting that spatial development encompasses two complementary strands. *Intra-object processing* refers to transformations that occur within a single object, whereas *inter-object processing* involves reasoning about spatial relations between multiple objects. For instance, consider the task of loading a cup into a dishwasher (See Fig.1.1 for more detail). Initially, we recognize and encode the cup (static) form, before mentally inverting it to place it upside down (dynamic); a transformation that reflects intra-object processing, as it involves manipulating the object relative to its own structure. Subsequently, we scan the dishwasher rack for other cups (static) and place the inverted cup in a position that takes into account the relative placement of the other cups, and in some cases, we may even adjust the positions of existing cups to maximize efficiency (dynamic). This manipulation relative to other objects exemplifies inter-object processing.

MR provides a clear illustration of intra-object processing in its dynamic form, as it requires mentally transforming an object's internal structure. Conversely, tasks that involve predicting an object's trajectory or its relative position to other objects reflect dynamic inter-object processing (Frick & Pichelmann, 2023; Frick et al., 2014). Despite their conceptual relevance, these two dynamic forms of intra- and inter-object processing are rarely investigated together. To date, few studies have examined the developmental links between these two strands in infancy; this issue is explored in detail in Section 1.2.4.

1.1.3 Historical Background and Classical Studies

Tracing the historical emergence of MR reveals how shifts in theory, method, and technology have transformed our understanding of spatial cognition and set the stage for current investigations into its developmental origins.

Historically, philosophers and psychologists conceptualised that there is a 'mind's eye' (Galton, 1880), which enables us to see objects that are not present in physical space. Later in the early 20th century, the modern term mental imagery (Galton, 1907; Kosslyn, 1980) entered the psychological lexicon, suggesting that humans can internally represent visual information in a way that preserves key properties of perception. The advent of the cognitive revolution led experimental psychology to explore this question and further investigate how mental representations vary depending on different viewpoints of the object (Kosslyn et al., 2006; Pearson, 2019; Pearson et al., 2015).

The classic study by Shepard and Metzler (1971) marked a turning point and gave rise to the concept of MR. In their task, the participants viewed pairs of perspective line drawings of 3D cube figures. Each figure was composed of ten cubes arranged in arm-like structures, with one figure in each pair either rotated within the picture plane or in depth relative to the other. The angular disparity between figures ranged from 0° to 180°, increasing in 20° increments. Participants judged whether the two figures were identical or mirror-reversed, responding as quickly and accurately as possible. The prevailing view of cognition during that time was that the brain functions as a serial digital computer and proposed that this task requires decomposing the objects into basic mathematical propositions and then mentally re-imagining. Under this view, it was expected that the time taken to decide whether the objects were the same or not would be independent of the degree of rotation. However, this view was challenged as Shepard and Metzler (1971) evidenced an opposite result: a linear relationship between the degree of rotation in the mental imagery task and the time it took participants to reach their decision. Error rates also rose slightly with angular disparity. It was concluded that participants performed a continuous MR of one object into alignment with the other to reach a same/different decision.

Subsequent models further refined the MR process. Just and Carpenter (1985) delineated MR as three distinct cognitive stages: (1) stimulus encoding into mental representation; (2) analogue MR to canonical alignment; and (3) comparison against stored prototype for identity/difference judgment. Following this, subsequent work by Shepard and Metzler (1988) and Heil and Rolke (2002) further differentiated the process into sequential stages: perceptual processing, stimulus identification and discrimination, orientation encoding, parity judgement, response selection, and motor response execution. This finding suggested that the human mind preserves and manipulates mental images as coherent, topographic and topological, which helped sharpen experimental designs and interpretive frameworks, allowing researchers to isolate the timing and neural correlates of MR itself from ancillary cognitive operations.

Through a series of neuroimaging studies, Kosslyn et al. (1978) demonstrated that when people visualise objects such as the letter "F," the corresponding mental image is represented, maintained, and rotated as a unified, image-like form within regions of the visual cortex. Furthermore, their work revealed striking similarities between the neural patterns activated by imagined stimuli and those elicited by actual perception. From these results, the researchers inferred that although the underlying neural mechanisms operate on mathematical and computational principles, the brain appears to be optimised for dynamically computing topologically structured images rather than constructing abstract mathematical models of objects.

The seminal cognitive studies on adult MR of the 1970s and 1980s (Cooper & Shepard, 1973) spurred interest in the developmental psychology field, with researchers trying to delve deeper into understanding how this ability develops in the early years of life: *When does MR first appear in life? How does it mature, and what factors shape its progression?*

Developmental theorists had explored related aspects of spatial cognition in early childhood and tried to answer these questions. Piaget's work emphasised that children actively construct their understanding of the physical world through sensorimotor interactions in infancy, which increasingly generate internal abstract representations in the preoperational stage (Piaget, 1952) Although Piaget did not isolate MR as a specific ability, his emphasis on the interplay between perception and action provided a foundation for later research linking motor experience with spatial reasoning (Pinquart et al., 2018). Complementing this constructive view, a nativist perspective proposed that spatial abilities are supported by innate structures that equip even infants with core knowledge about the layout of the environment (Spelke, 1998). From reaching toward a toy to predicting the path of a rolling ball, infants demonstrate early competencies rooted in spatial processing (Baillargeon et al., 1985; von Hofsten & Spelke, 1985). Together, these perspectives provide insights into the developmental foundations of spatial cognition and connect to broader adaptive mechanisms that shaped its evolutionary trajectory.

Before the 1960s, the perceptual capacities of infants were often underestimated.

Influential figures such as James (1890) and Spitz (1958) characterised the newborn's sensory world as "a blooming, buzzing confusion." This view began to shift with the methodological innovations of Fantz (1956), who introduced preference and habituation techniques to study perception in non-verbal populations. These methods revealed that even newborns can visually discriminate between different objects and faces, challenging earlier assumptions and laying the groundwork for developmental research into spatial cognition.

By the latter half of the 20th century, technological and methodological advances had broadened the scope of cognitive developmental research. Non-verbal tasks such as habituation–dishabituation, violation-of-expectation paradigms, and later, eye-tracking techniques enabled researchers to investigate cognitive abilities in preverbal populations more effectively without relying on explicit instructions (Baillargeon, 1987; Quinn & Liben, 2008). These innovations opened the door to exploring MR and other spatial abilities in the earliest stages of life, though infancy-specific findings will be addressed in detail in the following section 1.2.

1.1.4 Theoretical Background of Links Between Motor Skills and Spatial Skills

Learning to move independently marks a major milestone in the early years of life. The acquisition of self-produced locomotion, particularly crawling, represents a pivotal transition in infancy. As Campos et al. (2000) noted, the onset of self-produced locomotion orchestrates broad transformations across perceptual and cognitive systems by enabling infants to act upon and learn from their surroundings. Through autonomous control over movement in space, infants gain new opportunities for exploration, problem solving, and goal-directed behaviour (Gibson, 1988; Gibson, 2014). These experiences fundamentally differ from those of pre-locomotor infants, exposing them to diverse perceptual and cognitive challenges that promote developmental advancement (Witherington & Margett, 2011).

Theoretical accounts consistently show that perceptual and motor processes develop as an integrated system that supports adaptation and learning. Piaget's constructive theory (Piaget, 1952) proposed that knowledge arises from sensorimotor experience through repeated interaction with the environment, while Gibson's ecological perspective emphasised the inseparability of perception and action, suggesting that infants directly detect "environmental affordances" or action possibilities, through perceptual exploration (Costall, 1984; Gibson, 1970; Gibson & Pick, 2000). According to this theory, objects convey their functions through their perceptual properties, such as shape and spatial position, which infants intuitively use to understand the potential uses of objects. This dynamic reflects the continuous reciprocal relationship between bodily capabilities and cognitive development (Gibson, 1988), an approach that has since been expanded under the framework of embodied cognition (e.g., Needham and Libertus, 2011).

Embodied cognition posits that cognitive representations are grounded in sensory and motor systems, rendering cognition inseparable from physical experience (Serino & Ossmy, 2025). Similarly, dynamic systems theory views development as a self-organising process that emerges from interactions among biological, cognitive, motivational, and environmental factors (Thelen, 2005; Thelen & Smith, 1994). Within such frameworks, perception, action, and cognition form a unified adaptive system, with evidence showing that even abstract reasoning remains anchored in sensorimotor experience (Kontra et al., 2012).

This perspective aligns with broader shifts away from unidirectional, maturation-based models toward bidirectional frameworks in developmental science. Likewise, Gottlieb's theory of probabilistic epigenesis demonstrates that genetic, structural, and environmental factors continually co-act throughout development to shape neural and behavioural outcomes (Gottlieb, 1970). Experience thus plays an activity-dependent role: new motor skills, such as crawling, generate novel experiences that drive further developmental change (Gottlieb, 2007). Experience can induce new abilities, accelerate existing processes, or maintain established functions (Gottlieb, 1991), making locomotion both a typical and powerful pathway for cognitive progression.

Empirical evidence substantiates the interdependence of motor activity and cognitive development. Studies show that active object manipulation fosters more advanced object understanding. Needham (2000) found that 3.5-month-olds who frequently handled objects could better distinguish them as separate entities, while Libertus and Needham (2010) demonstrated that "sticky-mittens" training, allowing pre-reaching infants to grasp objects, enhanced their understanding of object separability. Similarly, Jovanovic et al. (2008) reported that haptic exploration improved infants' perception of objects as coherent wholes. These findings indicate that manual interaction promotes the development of mental representations that underpin higher-level visuospatial processes. Locomotor experience contributes similarly to spatial cognition. The onset of crawling allows infants to navigate independently, introducing new spatial and emotional experiences. Crawling infants outperform non-crawlers in spatial search and object permanence tasks (Clearfield, 2004; Kermoian & Campos, 1988). Schwarzer et al. (2013b) further demonstrated that infants with crawling or complex object-exploration experience could mentally rotate objects, whereas those without such experience could not (see Section 1.2.3 for more detail). Experimental training studies confirm this causal relationship: for example, Uchiyama et al. (2008) and Dahl et al. (2013) provided infants with locomotion training and observed subsequent improvements in perceptual and cognitive performance.

Consistent behavioural and neuroscientific evidence in adults supports this embodied relationship. Deutsch et al. (1988) found that MR increases cerebral blood flow in motor-related brain regions. Kosslyn et al. (1995, 2001) similarly proposed that shared neural resources for movement planning and MR reflect internal simulation of object manipulation. Behavioural data further show that body representation influences MR performance: in hand laterality tasks, reaction times increase with angular disparity and biomechanical difficulty (Parsons, 1987, 1994). Comparable results by Amorim et al. (2006) revealed superior MR performance for body-related compared to abstract stimuli, suggesting that anatomically plausible postures facilitate spatial transformations via embodied mechanisms.

Interference paradigms reinforce these findings. Wexler et al. (1998) and Wohlschläger and Wohlschläger (1998) demonstrated that manual rotations congruent with mentally imagined rotation directions enhance MR performance, whereas incongruent movements hinder it. Subsequent studies confirmed that even preparing for a manual rotation alters MR speed (Wohlschläger, 2001) and that motor cortex activation depends on the type of stimulus imagined (Sack et al., 2007). Such evidence demonstrates that MR engages motor simulation processes, with embodiment effects varying according to the degree to which visual stimuli correspond to bodily representations.

In summary, converging theoretical and empirical evidence supports the view that motor development could potentially be a driving force behind it. Across development, these embodied processes continue to shape higher cognitive functions, linking perception, action, and thought within a unified developmental system.

1.2 Infancy : Development of MR and Factors Influencing its Development

Infancy represents a critical period for the development of spatial skills and motor abilities, with major milestones emerging throughout the first years of life. From reaching for a toy, tracking a mobile, to locating a pacifier, nearly every action an infant performs is exploratory, gradually evolving from spontaneous movement to purposeful, goal-directed behaviour. Early movements are primarily reflexive, but by around three months, improvements in visuomotor coordination enable more controlled reaching behaviours (Clifton et al., 1993; Hospodar & Adolph, 2024; Lockman, 1990). These rudimentary actions provide crucial tactile and proprioceptive feedback that supports the gradual emergence of voluntary motor control (Striano & Bushnell, 2005; Zafeiriou, 2004).

Over time, reflexive grasping, initially triggered by palm stimulation, evolves into deliberate but imprecise pre-reaching movements (Karl et al., 2018a; Von Hofsten, 1986).

Infants begin to reach accurately toward visible targets and even anticipate the location of temporarily hidden objects, indicating early visuomotor integration (Karl et al., 2018b). Between 4 and 7 months, infants' movements become increasingly coordinated and rhythmic. Repetitive hand and finger actions, known as rhythmic stereotypies, reflect advancing motor control and mark the shift from spontaneous to purposeful movement. During this stage, infants begin to synchronise vision and manual activity, deliberately examining objects through coordinated hand-eye exploration (Adolph & Franchak, 2017; Connolly, 1998). By six months, reaching behaviour becomes finely tuned and visually guided, with infants adapting grasping strategies to the size and shape of target objects (Karl et al., 2019; Von Hofsten, 1986; Witherington, 2005). The development of postural control, including upright sitting and balance, further enhances visually guided exploration, precise object manipulation, and coordinated bimanual activity (Soska et al., 2010).

Concurrently, this period is also characterised by the maturation of several perceptual capacities that directly support object-based spatial cognition. Sensitivity to pictorial depth cues, including interposition, relative size, and linear perspective, emerges and consolidates between 6 and 7 months (Yonas & Granrud, 2006; Yonas et al., 1986), supplementing the binocular depth information available since approximately four months and providing infants with a richer, more robust perceptual basis for representing the 3D structure of objects. Importantly, the integration of multiple depth cues, rather than reliance on any single source, produces more stable and reliable depth precepts.

The onset of self-initiated locomotion, typically between 7 and 9 months, marks a major transformation in infants' spatial experience. Through crawling and other forms of movement, infants can actively explore their environment, perceive depth more accurately, and view objects from multiple perspectives (Adolph & Robinson, 2015; Campos et al., 2009; Witherington et al., 2005). Fine motor control also progresses rapidly during this period. By nine months, many infants can transfer objects between hands, rotate them, and explore their surfaces and edges, actions that enhance understanding of visuospatial relationships (Möhring & Frick, 2013; Soska et al., 2010). These developments underscore the dynamic interdependence between motor activity and spatial perception, as progress in one domain fosters growth in the other (Adolph & Franchak, 2017).

Contextual sensitivity in exploration also increases during the latter half of the first year. Infants aged six to ten months adjust their manual strategies according to environmental properties, such as pressing objects more often against flexible than liquid surfaces and showing preferences for soft over rigid materials Bourgeois et al. (2005). These findings suggest that infants can detect and exploit affordances, or action possibilities, within their surroundings. This adaptive responsiveness reflects emerging cognitive flexibility and the early integration of perceptual and motor systems essential for object understanding and problem-solving.

Overall, across the first year, motor behaviour and cognitive skills thus evolve, and this progression enables increasingly effective interaction with the environment and supports the development of higher-order perceptual and spatial abilities (Adolph & Hoch, 2019; Campos et al., 2012; Corbetta et al., 2018; Schwarzer & Jovanovic, 2015). This stage sets the stage for the emergence of 3D-MR and other forms of spatial reasoning, which are discussed in the following sections.

1.2.1 Paradigms Used to Measure MR in Infancy

Unlike adult MR paradigms, indirect methods are necessary to assess MR in preverbal populations. These approaches predominantly rely on gaze-based measures to infer infants' perceptual and cognitive processing. Traditional paradigms include violation-of-expectation methods (e.g., Frick et al., 2013a; Hespos and Rochat, 1997; Möhring and Frick, 2013; Rochat and Hespos, 1996), habituation procedures (e.g., Moore and Johnson, 2008; Quinn and Liben, 2008; Schwarzer et al., 2013b), change-detection tasks (e.g., Beckner et al., 2023a; Lauer et al., 2015), and eye-tracking techniques that provide spatial and temporal measures of visual attention (e.g., Pedrett et al., 2020).

Violation of Expectation

The Violation-of-Expectation (VoE) paradigm is grounded in the assumption that infants tend to look longer at events that are unexpected or surprising compared to events that are consistent with their existing knowledge or expectations. In a typical VoE paradigm, there are two phases, namely the familiarisation and test phase. In the familiarisation phase, infants are shown an event that has a predictable outcome, such as an object moving along a trajectory or rotating to a certain position. At the test phase, infants are presented with two types of outcomes: (a) expected outcome, which is consistent with physical continuity or the prior sequence, (b) unexpected outcome, which is inconsistent with physical principles or prior experience, thereby "violating" a postulated expectation. If infants reliably look longer at the unexpected event, it is inferred that they formed an expectation about what should happen and recognised when this expectation was violated. This increased looking time is taken as indirect evidence of underlying cognitive processes such as object tracking, reasoning, or, in the case of MR, tracking the orientation of an object while it is occluded.

Indeed, the first demonstrations of MR in infancy were using VoE by Rochat and Hespos (1996) and Hespos and Rochat (1997). In their study, 4-month-olds were shown a 2D T-shaped object rotating 180° in the frontal plane. In the first experiment, they showed the object pass through the occluder in the translational motion and revealed the object in the same or the inverted orientation (Fig 1.2a). In the second experiment, the object passed and rotated through 120°, behind an occluder (Fig 1.2b). When the occluder was removed, the object either appeared in the predicted orientation (if rotation had continued invisibly) or in an inverted, physically impossible orientation. In both conditions, infants looked significantly longer at the impossible orientation, suggesting that they mentally represented the 2D object's rotation and detected when the final orientation violated this mental model. These findings were interpreted as evidence for a rudimentary form of MR.

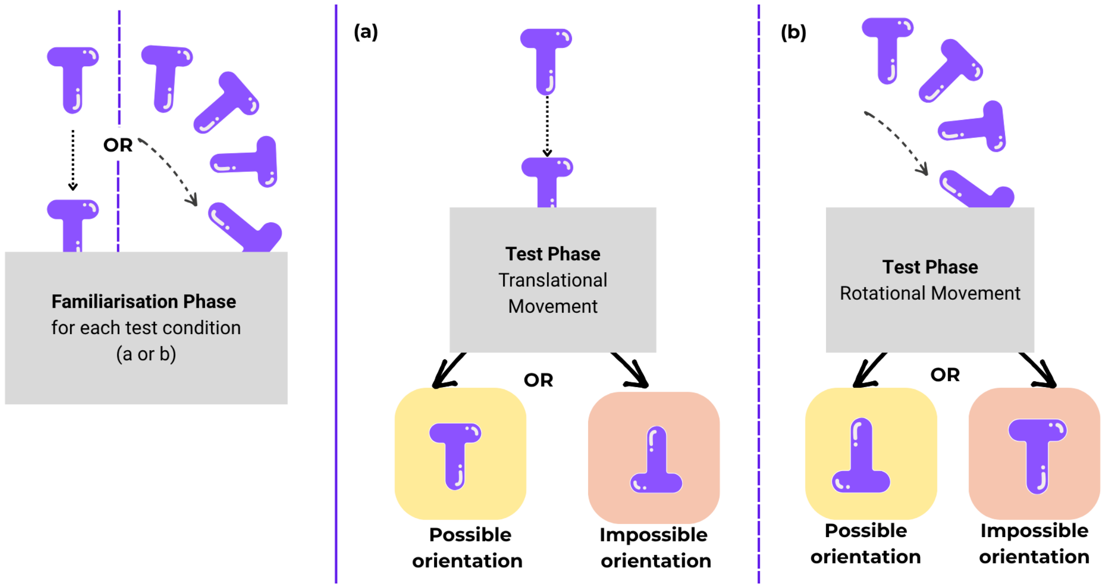

Figure 1.2: Example of the VoE paradigm. The extreme left shows the familiarisation phase for (a) translational movement and (b) rotational movement, with each test phase shown on the middle and right respectively. Longer looking times at the impossible orientation compared to the possible orientation (novelty preference) indicate surprise or that expectations about the object's rotation are violated. Figure adapted from Hespos and Rochat (1997).

Möhring and Frick (2013) further examined 6-month-old infants' ability to mentally rotate objects using a VoE paradigm. Infants observed an asymmetric object being lowered behind an occluder and subsequently reappearing as either the same object (possible event) or its mirror image (impossible event) in one of five orientations. Before testing, half of the infants received hands-on experience through manual exploration of the object, while the other half only observed it visually. Infants who engaged in manual exploration looked significantly longer at the impossible mirror-image outcome, indicating sensitivity to the object's orientation change. In contrast, infants with purely observational experience showed no differential looking across conditions. These results suggest that 6-month-olds' MR performance is facilitated by active motor interaction with objects, underscoring the critical role of sensorimotor experience in early spatial development.

Habituation Paradigm

Fantz (1956) introduced the preferential looking paradigm (also referred to as the looking preference method or head-turn preference procedure), in which infants are simultaneously presented with two contrasting stimuli and their visual fixation durations are compared. A consistent preference for one stimulus indicates that the infant can discriminate between them and shows an attentional or perceptual bias for the preferred option. Using this method, numerous studies have demonstrated that infants display spontaneous, pre-experimental preferences for specific types of visual stimuli.

Building on this approach, researchers later developed the habituation–dishabituation paradigm (Oakes, 2010). In this method, infants are repeatedly shown a stimulus until their visual attention declines, typically by 50 per cent relative to their peak looking time, indicating habituation or loss of interest. Once habituated, infants are presented with a novel stimulus. If they subsequently look longer at the novel stimulus than at the familiar one, this heightened attention is interpreted as evidence of discrimination and recognition. The difference in looking times between familiar and novel stimuli is used to infer either a familiarity or novelty preference, depending on which stimulus attracts more attention.

The first studies to investigate the development of MR using this paradigm were conducted independently by Quinn and Liben (2008) and Moore and Johnson (2008). In both studies, infants were habituated to specific visual stimuli and then tested with rotated versions of the habituated object alongside their mirror images. Quinn and Liben (2008) used a 2D stimulus: the numeral "1." After infants were habituated to this image, they were presented with rotated versions of the same number and its mirror image at novel orientations. Male infants demonstrated a novelty preference by looking longer at the mirror image, suggesting sensitivity to spatial transformation. This can be visualised in Fig 1.3 which represents the paradigm using a similar stimuli (letter p).

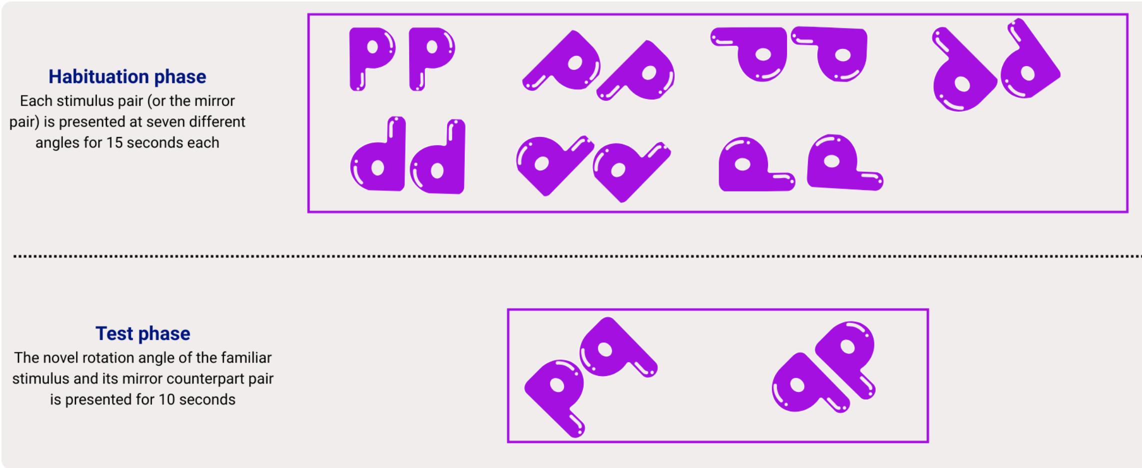

Figure 1.3: Example of 2D habituation paradigm. Longer looking times at the mirror image compared to the novel orientation of the familiarised stimulus (novelty preference) indicate that infants can discriminate the novel stimulus and may mentally rotate the familiarised representation. Figure adapted from Quinn and Liben (2008).

Moore and Johnson (2008) extended this work using a 3D adaptation of the Shepard-Metzler objects, rotating in depth (see Figure 1.4). Infants were habituated to an object rotating through 0° to 239°. During the test phase, they viewed the same object and its mirror image rotating through previously unseen angles (240°–359°). Again, male infants looked significantly longer at the mirror image, demonstrating a novelty preference. This was interpreted as evidence that the infants formed a mental representation of the habituated object, which they could mentally rotate to recognise it from new viewpoints. The preference for the mirror image thus suggested successful discrimination, implying that some rotation of the internal representation, either of the stored stimulus or the test display, occurred to enable comparison.

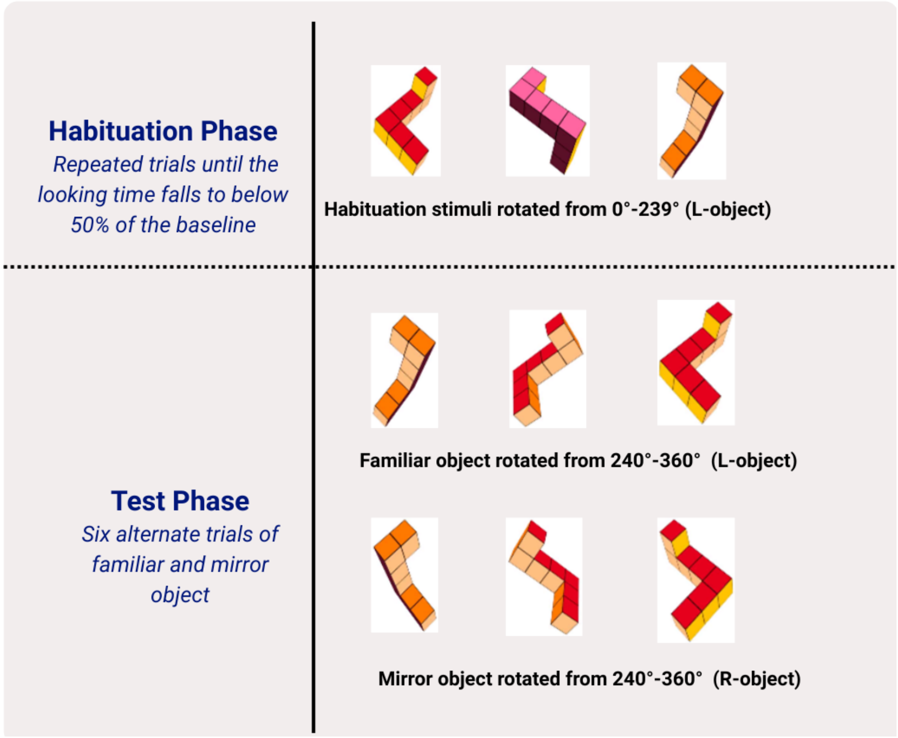

Figure 1.4: 3D habituation paradigm. Preference for the mirror object (R-object) indicates discrimination of the objects and possible MR of the habituated object. Figure adapted from Gerhard-Samunda et al (2021) based on Moore and Johnson (2008) paradigm.

Within the habituation-dishabituation framework, novelty preference is generally taken as evidence of MR ability. Conversely, a familiarity preference, longer looking toward the habituated stimulus, may indicate that encoding or processing is still incomplete, or that the task is cognitively more demanding. Both novelty and familiarity preferences have been documented throughout the first year of life, and their direction often depends on age and task complexity. Typically, younger infants (below about four months) are more likely to show familiarity preferences, while older infants tend to shift toward novelty preferences as cognitive and perceptual capacities mature.

A wide range of studies have applied habituation methodologies to explore MR in infancy (Christodoulou et al., 2016; Constantinescu et al., 2018; Gerhard & Schwarzer, 2018; Gerhard-Samunda et al., 2021; Moore & Johnson, 2011; Schwarzer et al., 2013a, 2013b; Slone et al., 2018). These studies generally present infants with video clips of unfamiliar, asymmetrical 3D objects rotating back and forth along an arc until habituation is reached. During the test phase, infants are shown either the familiar object rotating through a previously unseen angle or its mirror image doing the same. Both test items are novel in orientation, allowing researchers to measure whether infants distinguish the mirror image from the familiar object seen from a new perspective. Looking longer at the mirror image suggests discrimination and MR of one or both mental representations. Replications of this finding have been reported in diverse samples, including 5- to 6-month-olds (Constantinescu et al., 2018; Erdmann et al., 2018), implying that rudimentary MR abilities may emerge earlier than previously assumed. Moore and Johnson (2011), conducted a follow up study using identical methods and stimuli but with 3-month-old infants. Their results revealed a sex difference in younger infants as well: female infants looked at the two test stimuli for about the same amount of time, but the male infants looked longer at the habituation object in the new orientation than they did at the mirror-image object. Other investigations using similar methodologies have identified significant modulating factors such as motor development (Schwarzer et al., 2013b), which will be discussed in detail in another section.

However, not all studies have found a straightforward novelty preference. For example, Constantinescu et al. (2018) reported a significant novelty preference among 5-month-old boys using the traditional habituation setup, while Christodoulou et al. (2016), who adapted the paradigm to include a two-monitor display that increased task complexity, found a significant familiarity preference among 5-month-olds. Similarly, Erdmann et al. (2018) observed a familiarity preference among both male and female infants using the same method. These variations illustrate that novelty and familiarity preferences are not binary indicators but rather reflect developmental, methodological, and task-related influences.

Across the literature, both novelty and familiarity preferences have been used as sensitive behavioural markers of cognitive processing in infancy. In the context of MR, an increased interest in the mirror image is interpreted as an indicator of mental transformation processes, demonstrating that even early in life, infants exhibit the perceptual discrimination and representational flexibility foundational to spatial cognition.

Change Detection Paradigm

Lauer et al. (2015) adapted the change detection paradigm originally developed by Ross-Sheehy et al. (2003) for studying infants' visual short-term memory (VSTM), extending it to investigate infants' MR ability (see Figure 1.5). This procedure assesses whether infants can mentally transform object representations temporarily held in VSTM. During the task, infants view two side-by-side stimulus streams in which an object repeatedly appears, disappears, and then reappears in a new orientation. In one stream, the object undergoes a simple rotation, providing multiple views of the same object across different orientations. In the other stream, the object not only rotates but also appears as its mirror image, thus alternating between two distinct objects. If infants recognise the identity of the object across rotational changes, they are expected to show greater interest, indexed by longer looking times, toward the mirror-change stream. MR ability is therefore inferred from infants' preferential attention to the mirror-change over the non-mirror-change stream.

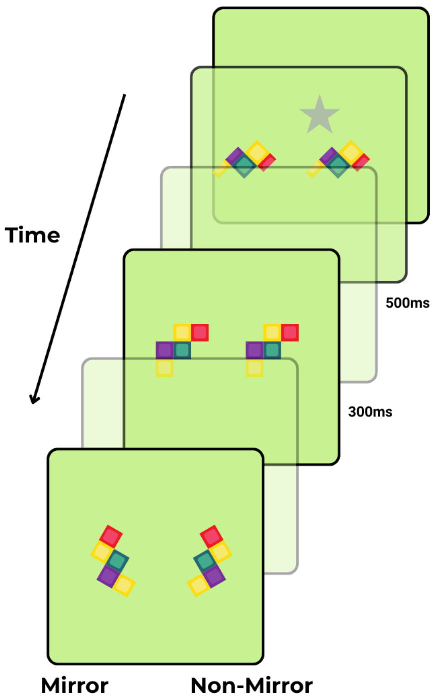

Figure 1.5: Overview of change detection paradigm. Sequence of events across time, with the left stream showing mirror stimuli and the right stream showing non-mirror stimuli. Figure adapted from Lauer et al. (2015); Beckner et al. (2023).

Beckner et al. (2023a) conducted two preregistered replications of Lauer et al. (2015) study using the same stimuli, procedures, and age range (6- to 12-month-olds), but with variations in task parameters and testing context. Experiment 1 was performed under controlled laboratory conditions, and Experiment 2 was administered online via the Lookit platform (Scott et al., 2017). Experiment 2 also included a within-subject manipulation to probe potential factors contributing to infant task difficulty. Despite methodological fidelity to the original procedures, both studies failed to replicate the MR effect observed by Lauer et al. (2015). Infants in neither experiment showed differential looking patterns indicative of MR. These results raise questions about the robustness of MR effects in infancy and highlight the sensitivity of change detection outcomes to subtle variations in procedure and context. Although change detection tasks have yielded convincing evidence of MR in some samples (Lauer & Lourenco, 2016; Lauer et al., 2015), replication failures underscore that MR competencies may be more fragile than initially assumed.

Similar inconsistencies have emerged in other paradigms. For example, Erdmann et al. (2018) found evidence of MR in 5- to 6-month-olds using a habituation paradigm but not in 9- to 10-month-olds, suggesting developmental or attentional influences. Given such divergent outcomes, meta-analytic approaches provide an important means to estimate the overall strength of the MR effect and to resolve inconsistencies across methods. A recent meta-analysis by Enge et al. (2023) synthesising 62 infant MR experiments involving more than 1,700 infants aged 3 to 16 months reported a significant overall effect, supporting the view that infants are capable of MR under at least some task conditions.

Action-based and Eye-tracking Paradigms

Örnkloo and von Hofsten (2007) examined how infants between 14 and 26 months understand spatial relationships between objects and openings. In this object manipulation task, children were asked to place blocks with different shapes, such as circular, square, rectangular, elliptical, and triangular cross-sections, into matching apertures. Solving the task required mentally rotating the object and using that spatial information to guide their movements. Each infant completed two types of trials: in half, the object was positioned upright, and in the other half, it was placed on its side. Results indicated that infants became consistently successful around 22 months of age. Successful problem-solving was linked to children's ability to adjust their hand and the object before reaching the opening, demonstrating planning based on MR. Additionally, no differences were found between girls and boys in performance.

Complementary evidence comes from Pedrett et al. (2020), who extended inquiry to toddlers aged 22 to 38 months. Employing a dual-method approach combining eye-tracking and behavioural paradigms, they demonstrated that toddlers exhibit nascent MR-like representations. In the eye-tracking task, toddlers observed simple geometric shapes rotating and temporarily disappearing behind an occluder. With increasing age, children exhibited more sophisticated gaze behaviours characterised by coordinated tracking of the rotating shape, anticipatory fixations toward the predicted point of reemergence, and reduced perseverative looking at the point of disappearance. Parallel behavioural assessments showed that older toddlers more accurately rotated blocks to fit through apertures, providing converging evidence of early mental transformation abilities. These implicit ocular and motor indicators collectively suggest that representational competencies related to MR begin to mature in the second year of life.

Taken together, the literature indicates that while MR can be detected in infants before their first birthday, its expression appears highly contingent on methodological parameters, task structure, and experiential factors such as motor activity and familiarity. These findings underscore both the promise and challenges of identifying early manifestations of spatial transformation abilities in infancy.

1.2.2 Sex Differences in Infant MR Tasks

Numerous studies of MR in adults have demonstrated robust sex differences favouring males, with meta-analyses confirming that the magnitude of this difference is large and consistent across studies involving the rotation of 3D objects through space (Linn & Petersen, 1985; Voyer, 1997). In contrast, findings from studies with young children and infants have been less consistent. Evidence from infants younger than one year remains mixed: some studies have reported sex differences, whereas others have not. Early precursory work did not reveal any such differences (Hespos & Rochat, 1997; Mash et al., 2007; Rochat & Hespos, 1996), yet the first two studies investigating MR in infants found male advantages (Moore & Johnson, 2008; Quinn & Liben, 2008). Subsequent research has produced similar results, with several studies reporting male-favouring differences in infants aged ten months or younger (Constantinescu et al., 2018; Kaaz & Heil, 2020; Lauer et al., 2015; Moore & Johnson, 2011; Quinn & Liben, 2014). In contrast, multiple other investigations have failed to identify sex-related effects in MR within this same age range (Christodoulou et al., 2016; Erdmann et al., 2018; Frick et al., 2013a; Gerhard & Schwarzer, 2018; Möhring & Frick, 2013; Schwarzer et al., 2013b; Slone et al., 2018).

1.2.3 Link Between Motor Skills and MR in Infancy

Role of self-produced locomotion in MR development

The onset of locomotion provides additional opportunities for perceptual–motor coupling. As infants begin to crawl, they experience the environment from new vantage points, gaining access to multiple spatial perspectives (Anderson et al., 2013). These experiences promote the integration of different viewpoints of familiar objects. Visual input generated by self-movement may thus be a key mechanism supporting the refinement of mental transformation abilities.

Research with infants has explored how MR development relates to motor abilities. Frick and Möhring (2013) showed that the capacity to walk with assistance among 8- to 10-month-old infants was strongly associated with MR success in a violation-of-expectation task. Using a habituation–dishabituation paradigm, Schwarzer et al. (2013a) reported that among 9-month-olds, only infants who had begun to crawl showed a clear preference for the novel mirror-image stimulus, indicating that locomotor experience supports MR performance. In a later study, Gerhard and Schwarzer (2018) further refined this relationship by manipulating the angular magnitude of object rotation. Nine-month-olds were habituated to an object rotating 180° around its horizontal axis, then presented with test rotations involving additional unseen angles of 90°, separated by gaps of 0°, 18°, 36°, or 54°. Results revealed that crawling infants, but not non-crawlers, showed reduced MR efficiency as angular gaps increased; small-angle transformations were easier to process. This finding suggests that crawling experience enhances the capacity for analogue mental transformations and that MR in infancy may also depend on task-specific demands, such as the degree of angular disparity.

However, not all findings are consistent. Erdmann et al. (2018), for example, found no evidence of MR ability or of a crawling-related advantage in 9-month-olds. Such null results highlight the variability in outcomes across studies and point to the need for systematic meta-analytic approaches to determine the overall robustness and magnitude of the MR effect.

Uchiyama et al. (2008) and Dahl et al. (2013) investigated the causal influence of self-produced locomotion on perceptual and emotional development in 7- to 8-month-old infants who had not yet begun to crawl. Infants were randomly assigned to either a locomotion-training or a control group. Those in the training group learned to move independently using a small, infant-sized powered mobility device (PMD) over 15 days, with daily 10-minute sessions. Across these studies, two primary outcomes were measured. The first was infants' motor compensation to perceived external motion, assessed by observing how much they adjusted their upper body movements in response to changes in peripheral optical flow within a moving-room apparatus. The second was their emotional response to height changes, measured by monitoring heart rate as infants were lowered over the shallow or deep side of a simulated visual cliff. The results provided evidence that the locomotion training significantly affected infants' postural compensation and their cardiac indications of wariness of heights. As the experimental design of these studies involved random assignment of pre-locomotor infants to either the PMD or a control condition not receiving any locomotion experience at all, locomotion experience can be understood as a significantly driving factor of the changes in the infants' responses to peripheral optic flow and wariness of heights.

To further assess this association in 3D-MR, Schwarzer et al. (2022) conducted a study with two groups of infants: a locomotion training group that received three weeks of training with a baby walker, and a control group. The performance of the MR habituation tasks was evaluated before and after the training period. The results revealed that only infants in the locomotion training group exhibited a significant change in their looking durations toward the mirrored image, suggesting that self-produced locomotion experience may positively influence infants' 3D-MR abilities. The results revealed significant differences between the training and control groups. Given the random assignment design, these findings provide compelling evidence that self-produced locomotor experience plays a causal role in modulating 3D-MR. These outcomes underscore how active movement reshapes infants' perceptual processing and adaptive responses to spatial cues.

Role of Manual Exploration in MR Development

A growing body of research indicates that infants' MR ability is closely linked to their manual experiences. Möhring and Frick (2013) examined this relationship in 6-month-old infants using a violation-of-expectation paradigm. Infants viewed videos showing an asymmetrical object, presented by a human hand, descending behind an occluder. After the occlusion, either the same object (a possible event) or its mirror image (an impossible event) reappeared in one of five orientations varying from 0° to 180° in 45° increments. Notably, infants did not observe any rotational movement before occlusion. Results revealed that infants displayed longer looking times toward the impossible outcomes only when they had been allowed to manually explore the test object before the task. Infants without prior manual experience were unable to discriminate between the two test conditions. These findings suggest that active hands-on experience enhances infants' ability to represent and mentally transform object orientations.

Frick and Wang (2014) extended these findings to older infants by adapting the violation-of-expectation approach for 14-month-olds. In their study, infants observed a toy on a turntable that underwent a complete but hidden rotation. The toy's final orientation was either consistent or inconsistent with the expected end position. Only infants who participated in a prior manual training session, during which they actively rotated a turntable with a different object, demonstrated longer looking times toward unexpected orientations. These two studies thus converge in showing that manual exploration supports the development of MR, whether through direct interaction with the test object or through exploratory training on a related task.

Slone et al. (2018) expanded on these findings using the sticky-mittens paradigm with 4-month-old infants. Half of the infants explored Velcro-covered objects before completing an MR task, enabling object manipulation despite their limited motor control. The other half engaged in object exploration only after completing the task. Using a habituation–dishabituation task with rotating Shepard–Metzler figures, the researchers found that infants who engaged in active exploration beforehand looked significantly longer at mirror objects, whereas those who explored afterwards did not. This pattern provides strong evidence that active manual exploration causally supports the emergence of MR abilities.

Building on these findings, Schwarzer et al. (2013b) investigated how both motor experiences, crawling and manual object exploration, relate to MR ability in 9-month-old infants. Crawling status and exploration levels were assessed using parental questionnaires and play-based measures, while MR was evaluated through a habituation–dishabituation paradigm featuring simplified Shepard–Metzler figures. During habituation, infants viewed an object rotating 240° around its longitudinal axis; during test trials, the same object or its mirror image completed the remaining 120° of rotation. Assuming a novelty preference, infants capable of MR should look longer at the mirror image, representing a novel orientation. Manual exploration skills were measured using five toy objects, which infants handled freely for 40 s each. Actions such as object rotations (≥ 90°), transfers between hands, and finger explorations were quantified. Consistent with this prediction, crawling infants preferred the mirror-image stimulus significantly more than non-crawlers. Among non-crawlers, low-exploration infants looked longer at the familiar object, likely reflecting incomplete encoding of the object's spatial structure, whereas high-exploration non-crawlers, like crawlers, preferred the mirror image, suggesting that manual experience can compensate for the absence of locomotor experience in supporting MR. These results suggest that manual exploration experience can enhance MR performance even in infants who have not yet developed independent locomotion.

Movement cues appear to play a central role in the emergence of MR abilities during infancy. As mentioned, Hespos and Rochat (1997) showed that infants aged 4 to 8 months benefit from orientation cues when processing rotational information. When a distinctively shaped object was presented within a scene, infants more easily detected both the direction and occurrence of rotation, suggesting that perceptual structure and movement cues support early spatial processing. Antrilli and Wang (2016) offered experimental evidence for the influence of self-induced visual motion cues on MR ability in 14-month-old infants. Their paradigm, adapted from Frick et al. (2014), familiarised infants with a fabric turtle rotating vertically behind an occluder. In test trials, a soft duck rotated either in the expected or unexpected direction. Before testing, infants engaged in an action phase, manipulating striped cylinders mounted on a rotating platform. The vertically striped cylinder generated complex, task-relevant visual motion cues, whereas the horizontally striped cylinder provided simpler, non-informative cues. As predicted, infants who experienced rotation with vertically striped cylinders subsequently showed a strong preference for the unexpected event, reflecting enhanced MR ability. Infants exposed to the horizontal pattern failed to differentiate between possible and impossible outcomes. Interestingly, these findings were extended by Gerhard-Samunda et al. (2021), who investigated whether these visual cues generated by manually rotating the cylinder could have an advantage in 3D-MR processing in crawling and non-crawling infants. Their results indicated an enhanced 3D-MR performance, which was indexed by a novelty preference in crawling infants who first presented with a vertically striped cylinder they manually explored but not with a horizontally striped cylinder, suggesting an association between MR and self-generated rotation-specific visual cues in crawlers. Furthermore, non-crawling infants didn't show signs of 3D-MR nor any advantage of the cylinder condition. These findings demonstrate that the complexity and task-relevance of visual cues derived from self-produced motor activity directly influence MR performance.

Kelch et al. (2021) investigated whether specific exploration procedures (related to crawling experience) support 3D-MR performance in 9-month-olds. In two studies, they examined the effects of manual rotation (Study 1) and haptic scanning (Study 2) on MR ability. They tested MR performance using a live experimental set-up based on the task used by Moore and Johnson (2008). Results show that, after manual rotation experience with a target object, crawling infants were able to distinguish between exploration objects and their mirror objects, while non-crawling infants were not (Study 1). Infants who were given prior experience with objects through haptic scans (Study 2) did not discriminate between objects, regardless of their crawling experience. Results indicated that a combination of manual rotations and crawling experience is valuable for building up the internal spatial representation of an object.

Collectively, the findings across these studies converge on the conclusion that motor experience, both manual and locomotor, plays a causal and facilitative role in the emergence of MR during infancy. Active interaction with objects, either through manual exploration or self-generated movement, appears to strengthen infants' ability to mentally represent and manipulate spatial information. These findings also indicate that the experiences gained through crawling and manual exploration may partially substitute for one another, as both offer infants opportunities to view objects from multiple perspectives and integrate spatial relations through active engagement (Schwarzer, 2014).

Despite the considerable progress made in understanding the relationship between motor experience and MR in infancy, several methodological limitations constrain the conclusions that can be drawn from the existing body of evidence. The predominance of cross-sectional designs with narrow age ranges limits insight into the longitudinal continuity of MR and the stability of individual differences across developmental stages. Furthermore, the majority of existing studies have examined motor experience and MR in isolation at single time points, making it difficult to determine whether early motor-spatial associations reflect transient, age-specific phenomena or enduring developmental relationships that persist and evolve across the early years of life. Addressing these limitations represents an important next step for the field.

1.2.4 MR, Visual Prediction and Locomotion in Infancy

As mentioned by Newcombe et al. (2013), inter-object processing, such as visual prediction, is also an important spatial skill. Studies have shown that as early as two to three months of age, infants begin to exhibit rudimentary predictive eye movements. Wentworth and Haith (1992) demonstrated that infants at this age can anticipate the location of visual stimuli when the hiding sequence follows a predictable and temporally regular pattern. Extending these findings, Wentworth et al. (2002) found that 2- to 3-month-old infants are sensitive to spatiotemporal regularities and can use interevent contingencies to forecast the position of subsequent visual events, indicating an early capacity to detect and learn from environmental patterns and regularities. Another famous demonstration, the A-not-B error task, is used to measure this ability. In this paradigm, infants repeatedly retrieve a hidden object from one location (A) but continue to search there even after observing it being hidden in a new location (B). Although such behaviour appears erroneous, it reflects developing expectations about object location and movement and reveals early attempts to use perceptual experience for prediction.

Several stimulus-related factors influence the efficiency of visual prediction, including occlusion duration, object velocity, and the way objects disappear from view. Von Hofsten et al. (2007) and Gredebäck and von Hofsten (2004) found that faster or shorter occlusions substantially reduce infants' ability to accurately generate anticipatory eye movements, suggesting that temporal predictability is critical for maintaining continuity in object tracking. Building on this work, Spelke and von Hofsten (2001) examined how 6-month-old infants anticipate objects' reappearance following occlusion along both linear and non-linear trajectories. In their experiment, a toy moved across a screen and disappeared behind a central occluder, either continuing in a straight line or abruptly changing horizontal direction mid-path. Results showed that infants readily anticipated linear trajectories but were slower and less accurate in predicting non-linear ones. This pattern suggests that infants possess a natural bias toward linear motion extrapolation and require experience to learn more complex, non-linear trajectory predictions.

Collectively, these findings demonstrate that visual prediction abilities emerge early and evolve from basic pattern recognition to more sophisticated motion extrapolation mechanisms (Nagai, 2019). This developmental trajectory reflects the interplay of perceptual learning, temporal attention, and sensorimotor coordination, which together enable infants to anticipate and interact with a dynamic visual world.

A substantial body of research has also focused on the relationship between infants' ability to locate hidden objects and their locomotor experience. Early studies consistently showed that active, self-produced movement facilitates infants' ability to track and retrieve hidden objects. Acredolo et al. (1984) trained 12- and 18-month-old children to find an object hidden in one of two identical wells inside a Plexiglas box and found that only 18-month-olds who actively changed their position successfully located the hidden object. Similarly, Benson and Užgiris (1985) reported that 10- to 11-month-old infants could find a hidden object only when they crawled independently to a new location rather than being passively carried. Kermoian and Campos (1988) extended these findings by showing that 8.5-month-old infants with more crawling or walking experience performed better in a series of object permanence tasks, including spatial search. Performance improved with both the duration and quality of locomotor experience; hands-and-knees crawlers and walkers outperformed belly crawlers. Comparable relations have also been observed in special populations: Campos et al. (2009) found that in infants with spina bifida, the onset of crawling was linked to improved performance in a two-position manual search task. Similarly, Bai and Bertenthal (1992) showed that only crawling 8-month-olds, but not same-aged non-crawlers, correctly identified the location of a hidden toy after being repositioned to the opposite side of a table, providing further evidence that self-generated movement facilitates spatial updating.

While these studies measured spatial competence through overt motor responses, more recent work has investigated whether similar motor–cognitive relationships appear in infants' gaze behaviour. Using a live eye-tracking version of an occlusion paradigm, Kubicek et al. (2017b) examined predictive gaze behaviour in 9-month-olds. During familiarisation, a 3D object rotated back and forth along a vertical axis, briefly occluding and revealing two target areas with each change in direction. During the test phase, the object rotated horizontally, and the targets either remained in their original positions or were shifted to new locations. Predictive gaze (i.e. looking toward the location of a target before it became visible) was assessed as an index of anticipatory spatial processing. Crawling infants exhibited significantly more predictive fixations than non-crawlers, especially under increased task demands, suggesting that locomotor experience enhances infants' ability to form dynamic mental representations of objects.

A related study by Kubicek et al. (2017a) explored the link between manual object exploration skills and object-location prediction. Seven- to eight-month-old infants were tested in a comparable occlusion paradigm and additionally participated in a manual exploration task in which they freely manipulated five objects varying in shape and texture. Infants' exploratory actions, such as rotations, hand transfers, and finger manipulations, were coded as indicators of manual skill. The findings revealed that infants with higher levels of manual exploration proficiency were more successful in predicting target reappearance locations. These results imply that hands-on interaction with objects facilitates the development of coherent spatial representations by allowing infants to perceive objects from multiple viewpoints and to integrate visual, tactile, and proprioceptive information.

Taken together, the combined findings from both locomotor and manual exploration studies indicate that infants' ability to locate, track, and predict the position of objects is closely linked to their motor experience. Self-produced movement appears to facilitate the integration of spatial information, the transition from egocentric to allocentric coding, and the refinement of anticipatory attention and working memory (Anderson et al., 2013; Campos et al., 2000).

However, very limited studies have aimed to link inter- and intra-object processing. One attempt by Pedrett et al. (2020) highlights the developmental progression of toddlers' anticipatory and MR abilities. In the eye-tracking task, anticipatory looks to the location where a rotating object was expected to reappear increased between two to three years of age, while looks back to the disappearance location decreased, indicating that toddlers develop a more robust expectation of the object's trajectory rather than merely responding faster. This finding demonstrates that anticipatory eye movements, reflecting inter-object processing, continue to mature during toddlerhood and provide a window into the formation of mental representations of object movement. In contrast, the VoE paradigm used to assess MR (intra-object processing) did not yield significant evidence of MR in toddlers, nor did it correlate with other task measures. Several factors could account for this null result, including insufficient salience of task-relevant features, lack of engagement, or limitations of looking-time measures for capturing MR at this age. Additionally, using a behavioural object-fitting task to measure MR, the study revealed that anticipatory processing and action planning are closely linked. Toddlers who better anticipate the object's reappearance also plan rotations of wooden blocks more accurately, suggesting that the development of visual anticipation and emerging MR abilities may operate in tandem, supporting the broader acquisition of spatial cognition in early childhood.

1.3 Preschool Years: Development of MR and Motor Contributions

Preschool years, spanning from the age of 4 to 6, are a critical developmental window for both spatial cognition and motor abilities, especially because these years prepare children for school entry. Around age 4, children begin to reliably use spatial terms such as above, below and behind, follow complex spatial and motor instructions, and engage in symbolic play that requires maintaining mental and physical representations (Frick & Möhring, 2016; Newcombe & Huttenlocher, 2000). Simultaneously, they develop gross motor skills, including strength, balance, and agility, through activities like running, jumping, climbing, riding tricycles, and balancing on beams. These movements become more coordinated and intentional, providing the foundation for increased bodily control and exploration (Cortes et al., 2022; Morawietz et al., 2024). Their fine motor skills advance, enabling activities like drawing shapes and buttoning their clothes, copying shapes, building block towers, using scissors, and handling small utensils. These skills not only support self-care, like dressing up, brushing teeth, but also facilitate academic tasks such as handwriting and puzzle solving, relying on precise hand-eye coordination (Del Giudice et al., 2000; Morawietz et al., 2024).

A key milestone in this period is the emergence of writing skills. Many preschoolers can write their names, a significant step in literacy that integrates motor precision, spatial sequencing, and symbolic understanding (Dinehart & Manfra, 2013; Puranik & Lonigan, 2012). Additionally, at this age, children show growing proficiency with digital technology tools requiring fine motor coordination, such as tablet tracing, mouse control, and simple keyboard use, reflecting the evolving demands of contemporary learning environments (De Lisi & Wolford, 2002). These advances emphasise embodied learning, fostering abstract thinking and cognitive flexibility (Newcombe & Huttenlocher, 2000).

In sum, the preschool years are crucial for the integrated development of spatial reasoning and motor skills. Supporting these emerging capacities and specifically understanding the development of MR is essential not only for successful school transition but also for cultivating the physical, cognitive, and social skills necessary for creative, adaptive, and independent living throughout life (van der Fels et al., 2015; Zeng et al., 2017).

1.3.1 MR in Preschool Age

As compared to infant studies, research on MR in preschoolers is relatively sparse. Most of the existing studies that have investigated the development of MR in populations between the ages of 4 and 12 years (Iachini et al., 2019; Kail, 1991; Kail et al., 1980; Marmor, 1975; Titze et al., 2010) have used cross-sectional designs.

Early Studies on MR in Preschoolers

Piaget and Inhelder's influential stage theory of cognitive development posited that young children struggle to imagine the consequences of spatial transformations unless they have physically performed those transformations themselves (Gallagher & Reid, 2002). According to this interpretation, MR is not expected to fully emerge until children enter the concrete operational stage, which is at approximately 7 to 8 years of age. However, this was challenged by the pioneering work of Marmor (1975), who proposed that children below 7 years possess MR if child-friendly tasks are used. Marmor modified the classical Shepard-Metzler paradigm (1971) for children and tested 5-year-olds and 8-year-olds by using 2D pictures of a bear-shaped figure. The stimuli were presented in pairs with either only the left or right arm raised in both figures, or with different arms raised in both figures. The children first participated in a pre-training session where they were asked to state if the presented pairs were 'same' or 'different' based on the raised arm of the bear. The test phase consisted of 60 trials wherein one bear was presented upright on the left side, and the second bear rotated at one of five angles (0°, 30°, 60°, 120°, or 150°) on the right. The children were instructed to judge if the two bears were the same or different by rotating them in their minds and pressing the corresponding lever to indicate their response as fast as possible. RT served as an indicator of MR ability. The results revealed a clear linear increase in RT as angular disparity increased, mirroring findings in adults. As expected, younger children had higher RTs compared to the older children. Marmor concluded that children as young as five years of age are capable of performing dynamic mental transformations akin to adults, with the time taken to respond reflecting the mental effort required to rotate the image to the upright position. Marmor (1977) replicated and extended these findings in a later study, introducing ice cream cone stimuli with missing sections to further confirm children's sensitivity to MR demands.

Dean and Harvey (1979) offered an important extension of this work by systematically examining MR performance across three age groups (4 to 6; 7 to 9; 10 to 14 years), using a RT adaptation of Piaget and Inhelder's rotating squares imagery task. Their findings revealed that while the youngest children showed limited evidence of a systematic, analogue MR strategy, the two older groups displayed clear linear increases in reaction time as a function of angular disparity. Moreover, although analogue strategies tended to be associated with greater accuracy, the results indicated that some children could achieve high accuracy through other, potentially less effortful approaches. Kosslyn et al. (1990) further reinforced that children as young as five years of age possess the ability to mentally rotate 2D figures. However, their RT was markedly higher compared to older children and adults. Specifically, 5-year-olds demonstrated slower rotation speeds than 8-year-olds, who in turn were slower than 14-year-olds and adults, indicating a clear developmental progression. Complementing these findings, Kail et al. (1980) examined MR in various age groups, ranging from fourth to sixth graders and adults, using alphanumeric characters and abstract symbols. Their results revealed that RT increased linearly with greater angular disparity, replicating the previous findings of Marmor (1975).

Furthermore, Estes (1998) conducted a study structured similarly to Marmor (1975) but with a particular emphasis on the role of instruction. Children aged 4, 6, and adults participated and were asked to identify whether pairs of images were the same or mirror images, without any explicit instruction to use MR. After the task, participants were asked to explain how they made their decisions. Results showed that 6-year-olds spontaneously used MR without instruction, similar to adults. Four-year-olds who referred to mental activity in their explanations also showed RT patterns consistent with MR, whereas 4-year-olds who did not mention mental activity responded randomly, indicating no use of MR. In a follow-up study, Estes concluded that young children could access and report on some types of mental activity earlier than previously thought, and that awareness of one's thinking strategies plays a key role in task performance.

Taken together, these relatively early studies underscore a developmental trajectory in which both the accuracy and speed of MR improve with age and demonstrate that children below seven years possess MR ability, which is contrary to Piaget's original suggestion, while also emphasising the importance of task complexity and stimulus type in assessing children's spatial cognition.

Experiments with an action-based task

Some studies investigated whether children under five possess MR ability. However, earlier studies with children relied on the same-different judgment tasks requiring manual responses, which impose high cognitive demands. Recent research, therefore, adopts action-based paradigms that minimise cognitive load and employ embodied responses like pointing or object manipulation. By tailoring task complexity and response demands, these approaches enable more accurate assessment of MR in children under five, maintaining accuracy and RT as primary indicators. As knowledge about objects is most effectively acquired through sensorimotor or action-based experiences, creating a tangible, hands-on experimental setup could be instrumental in understanding how children form mental representations of objects (Kosslyn et al., 1978, 2006).

Krüger et al. (2014b) were among the first to demonstrate MR abilities in children as young as 3.5 years using a novel touchscreen paradigm (see Fig. 1.6). In their study, children were presented with pairs of images, one of which was rotated by varying angles (45°, 90°, 135°, 180°, 225°, 270°, or 315°). Children were instructed to manually rotate the displaced image back to its upright orientation using the shortest possible path. RT until touching the stimulus (handle) were recorded as the key metric. The results showed a reliable linear increase in reaction time corresponding with larger angular disparities, providing behavioural evidence for analogue MR processes even at this young age. A follow-up experiment further clarified that this linear increase in RT was contingent on the requirement to use the shortest rotation path, demonstrating that mere manual planning could not fully explain the observed effect. This finding indicates that MR in young children involves integrated cognitive and motor planning beyond simple physical manipulation, thereby challenging traditional views on the developmental timeline for spatial transformation skills.

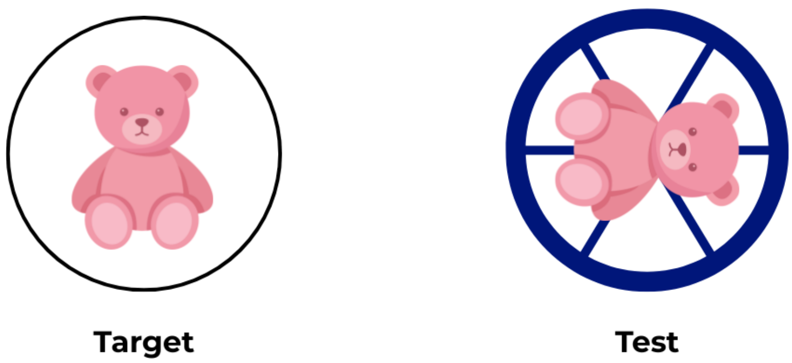

Figure 1.6: Example of a stimulus configuration where participants were asked to 'straighten out' the rotated stimulus. Children would touch the handle placed around the right stimulus and drag the bear along. Figure adapted from Krüger et al. (2014).

A seminal contribution in this field was made by Frick et al. (2013b), who developed a novel MR task specifically designed for children between 3 to 5 years (Fig. 1.7). The task consisted of two asymmetrical ghost figures that were mirror images of each other and were simultaneously presented alongside a cutout corresponding to one of the ghosts. Children were instructed to select and physically fit the correct ghost figure into the matching cutout, enabling immediate, tangible feedback on their choices. Results demonstrated clear age-related improvements: none of the 3-year-olds and only some 4-year-olds performed above chance, while the majority of 5-year-olds succeeded at rates significantly exceeding chance levels. Critically, performance declined with increasing angular disparity between the ghost figures, consistent with the cognitive demands of MR. To further investigate the role of embodied interaction, a second version of the task was administered using a 2D paper format, where the ghosts could not be physically manipulated but were static images printed on a sheet. Although some 4-year-olds and most 5-year-olds also performed above chance on this version, the proportion of above-chance performers was significantly lower compared to the interactive task. These findings highlight the facilitative effect of tangible, manipulable stimuli in reducing task complexity and enhancing developmental appropriateness.

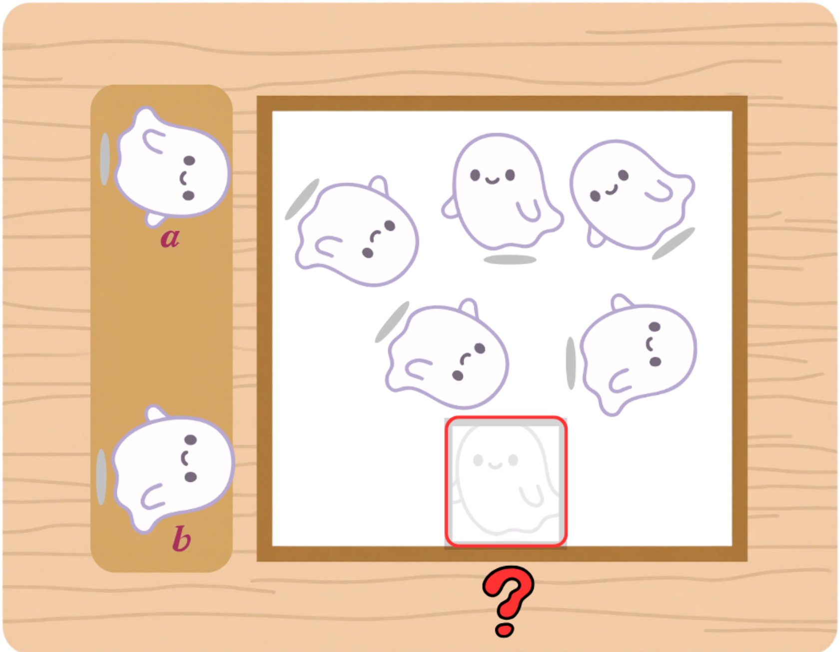

Figure 1.7: Ghost task. Two asymmetrical, mirror-reversed ghost pieces (left) and a board with an empty hole for one of the ghosts (right) were shown, and the child was asked to fit the correct ghost of the two. Figure adapted from Frick et al. (2013b).

Further advancing the developmental understanding of MR, Pedrett et al. (2020, 2023) employed a multimodal approach combining eye-tracking and behavioural methods to examine mental representations of object rotation in children aged 3.5 to 5.5 years. In their task analogous to the VoE paradigm, children observed asymmetrical, flag-shaped figures rotating before briefly disappearing behind an occluder and subsequently reappearing either in their original orientation or as mirror-reversed images. Eye-tracking analyses revealed an age-related increase in gaze sophistication, characterised by coordinated tracking of the rotating stimulus, anticipatory saccades directed towards the expected point of reemergence, and diminished fixation on the disappearance locus. Complementing this, a behavioural novel MR task was presented to the children. The task consisted of paired boards, each containing a cutout and a flag figure, which were either congruent or mirror-reversed. The participants were instructed to mentally rotate the figure to determine the correct board before physically fitting the flag into the cutout. The angular disparity between figures varied systematically. Findings indicated that all participants could successfully distinguish the figures, with younger children (3.5–4 years) demonstrating MR capabilities up to 150° and older children (4–5.5 years) up to 180°. Notably, no significant correlation emerged between performance in the predictive eye-tracking task, looking time in the eye tracing task and the success rate in the behavioural MR task, suggesting that predictive eye movements and looking-time measures may not fully capture the cognitive processes underlying MR during dynamic rotational movements. This dissociation implies that these tasks engage distinct cognitive mechanisms, potentially reflecting differential processing of inter-object versus intra-object spatial representations. Importantly, this study opens promising avenues for future research exploring the multifaceted nature of spatial cognition and the distinct cognitive substrates that support diverse facets of visuospatial processing.

A notable attempt to develop an age-appropriate MR task using 3D objects was made by Hawes et al. (2015a), who used tangible blocks with 4-to-8-year-olds. They presented four test objects: a target object, a rotated object, a mirror object and a structurally dissimilar distractor. Each trial began with presenting an occluder to shield the view of the test items. from view. Prior to revealing the figures, participants were instructed to look carefully at the three options below the target and point to the item that matched the target. Once the occluder was removed and an item was selected, participants were asked to place the item to the right of the target and demonstrate how it could be made to match the target. This same procedure was repeated for all 16 items (see Fig 1.8). Performance was shown at three levels: (i) successful rotators; (ii) mirror confused; (iii) guessers. While older children had lower error rates and were successful rotators, the 5-year-olds performed above chance level, and most of them were mirror-confused. Although a correlation between the 2D Children's Mental Transformation Task (CMTT) by Levine et al. (1999) and 3D tasks were found, the effect of angular disparity, a hallmark indicator of MR, was not investigated, highlighting the imperative need to carry out comprehensive research on 3D-MR in preschoolers.

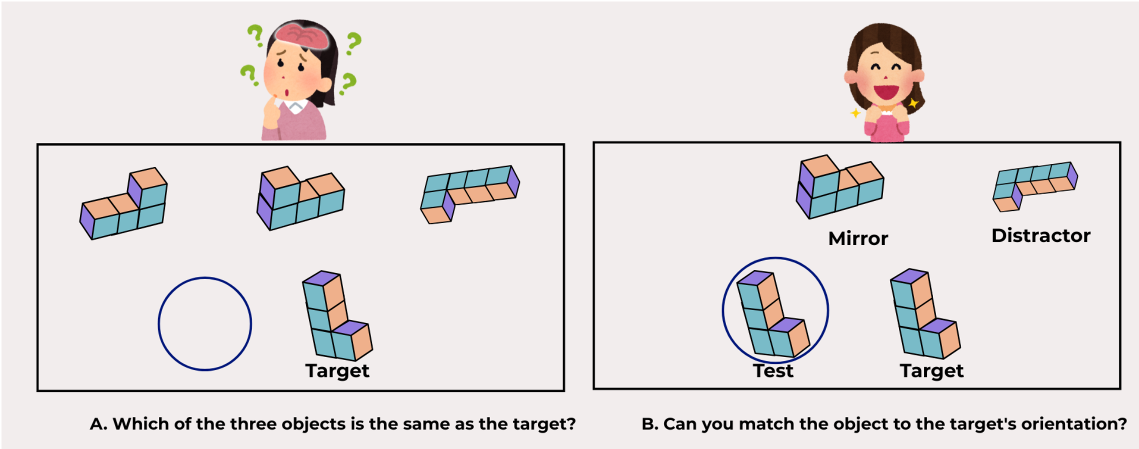

Figure 1.8: Tangible block task. Three objects are presented, and the child is asked to match the correct object of the three to the target. Figure adapted from Hawes et al. (2015a).

Overall, using diverse paradigms, such as interactive touchscreen tasks, puzzle manipulations, and eye-tracking studies, foundational MR abilities appear around age three in implicit or action-based contexts, while consistent performance becomes evident by age five. Task constraints and the nature of the stimuli seem to play a major role in detecting MR effects.

MR Training Studies

As multiple meta-analyses have established that MR exhibit notable plasticity, and can be significantly improved with targeted practice, with training effects often generalising beyond the trained tasks (Baenninger & Newcombe, 1989; Uttal et al., 2013). Levine et al. (2012) demonstrated that children aged 2 to 4 years who frequently engaged in spatial activities such as puzzles performed better on spatial transformation tasks, with a positive correlation between puzzle play frequency and spatial skill levels. Despite this, high-quality MR training studies involving preschoolers remain limited, creating gaps in understanding the optimal timing and conditions for skill acquisition. Some early evidence by Ehrlich et al. (2006) reported that 5-year-olds enhanced their MR skills after six training trials requiring the selection of a composite figure from alternatives. In contrast, Marmor (1977) classic study showed no effect of MR training in 4- and 5-year-olds following seven training trials, highlighting variability in outcomes contingent on experimental design. A replication by Platt and Cohen (1981) revealed significant training effects under a comparable protocol, with methodological refinements including the addition of salient visual cues and less restrictive inclusion criteria accounting for some of the disparity. This underscores the importance of study design, participant selection, and pretraining procedures in evaluating MR trainability. Recent research has reinforced MR training in preschool-aged children using more comprehensive, developmentally tailored interventions. A recent study by Fernández-Méndez et al. (2018) examined the efficacy of MR training and potential sex differences in two cohorts of preschoolers: younger children aged 3 to 4 years (Experiment 1) and older children aged 4 to 5 years (Experiment 2). Participants were randomly assigned to either a training or a control group. The training group received three sessions of training using the versions of the Frick et al. (2013b). MR was measured using the modified version of the Picture Rotation Task (Quaiser-Pohl, 2003), distinct from the training exercises, ensuring measurement of transfer effects. Results indicated significant improvements in MR performance among the older preschoolers following the intervention, with a trending but non-significant enhancement in the younger group. Importantly, no sex differences were observed in MR ability or in training-related gains across age groups, supporting the notion that spatial skill malleability is evident early in development and is not inherently sex-linked. These findings have important educational implications, emphasising the need to incorporate spatial skills training within early childhood curricula and to foster gender equity in spatial cognition development. Such efforts could contribute to reducing the persistent under representation of women in STEM fields and career paths strongly reliant on robust spatial abilities (Li et al., 2021).

In a subsequent study, Fernández-Méndez et al. (2020) extended this exploration to children in 1st (3–4 years) and 3rd year (5–6 years) of preschool education, focusing on both training effects and developmental trajectories of MR. Their results demonstrated significant MR gains in the older (3rd year) trained group, with marginal improvements in the younger cohort. Notably, the older children exhibited lower error rates during training and a more robust capacity to overcome increased angular disparities compared to the younger group, whose performance declined linearly as angular disparity increased. Furthermore, improvements were most pronounced among 5-6-year-olds with lower initial MR abilities, indicating that training is particularly beneficial for children starting with weaker spatial skills. Together, these studies emphasise that MR is a developing spatial ability amenable to intervention during preschool years and that early targeted training can effectively enhance this critical cognitive skill, particularly in children with initial deficits.

Hawes et al. (2015b) conducted a randomised controlled trial with children aged 6 to 8 years, who were randomly assigned to either computerised MR training or a control literacy training group. Over six weeks, integrated into regular classroom activities, children in the spatial training condition, using iPad-based tasks, demonstrated significant improvements on measures of MR and marginal improvements on untrained mental transformation tasks. These results indicate that MR training can elicit generalised gains in spatial reasoning. However, contrary to predictions and previous findings suggesting that spatial training facilitates mathematics performance (Mix et al., 2021), no transfer effects to mathematics outcomes were observed in this sample. This aligns with earlier meta-analytic conclusions by Uttal et al. (2013), highlighting mixed evidence regarding far transfer effects of spatial training programs.

Collectively, these findings highlight that MR abilities in preschoolers are both emergent and malleable, with training effectiveness dependent on developmental readiness, intervention dosage, and the incorporation of embodied learning experiences. These insights advocate for integrating spatial skill training into early educational curricula to support foundational cognitive development with potential long-term academic benefits. can be significantly improved with targeted practice, with training effects often generalising beyond the trained tasks (Baenninger & Newcombe, 1989; Uttal et al., 2013).

1.3.2 Sex Differences in MR Tasks in Preschoolers

Early research by Caldwell and Hall (1970), Jahoda (1979), and Kaess et al. (1974) consistently reported no significant sex differences in MR performance among children younger than ten years, suggesting that the male advantage often observed in adults has not yet emerged or may be masked by developmental factors at this age. Still, several investigations have reported exceptions to this pattern. Krüger and Krist (2009) found higher error rates among boys on certain MR tasks, whereas Levine et al. (1999) detected sex differences only in children older than 4.5 years, hinting at a potential developmental window when disparities begin to appear. In line with Voyer (1997) meta-analysis, which concluded that reliable sex differences in MR typically do not emerge before about ten years of age, more recent work by Krüger et al. (2014a) likewise found no sex-related differences in MR among preschoolers.

A systematic study by Jansen et al. (2013) provided more nuanced evidence. Testing second and fourth-grade children with a range of stimuli, including animal drawings, letters, and cube figures, the researchers found that cube figures, even when rotated in the picture plane, were excessively difficult for both age groups. However, when stimuli were developmentally appropriate, such as animal drawings or letters, a robust male advantage emerged in both reaction times and accuracy. RT increased systematically with angular disparity for all participants, and older children responded faster than younger ones. This study was the first to demonstrate consistent sex differences in chronometric MR tasks in primary school children, underscoring the critical role of stimulus selection in detecting developmental and sex-related effects in spatial cognition.

Complementary evidence from neuroimaging and electrophysiological research suggests that neural differentiation by sex may precede behavioural differences. Hahn et al. (2010) identified distinct neural activation patterns during MR tasks in preschoolers: boys showed bilateral engagement of parietal regions, whereas girls exhibited more left-lateralized activation. Such findings imply that cognitive processing strategies may differ early in development, potentially channelling sex-specific pathways of spatial cognition before overt performance gaps emerge.

Beyond biological explanations, psycho-social factors substantially shape spatial development. Ebert et al. (2024) found that gender stereotypes linking spatial ability with boys are already internalised by ages four to six. Boys were more likely than girls to endorse these stereotypes, though the effects on task performance were complex. While stereotypes were not directly associated with overall MR accuracy, implicit stereotype strength was related to higher MR performance in girls but lower accuracy in boys. This pattern may reflect motivational or confidence-related mechanisms shaped by socialisation rather than intrinsic ability differences. The authors also emphasised that early experiences and family attitudes toward spatial play interact with self-concept and engagement, influencing how children persist in spatial tasks.

Environmental and intervention-based evidence further demonstrates that equitable access to spatial learning experiences can mitigate potential disparities. Previously mentioned training studies by Fernández-Méndez et al. (2018) showed that intensive MR training in preschool settings improved performance equally in boys and girls. These results suggest that when spatial opportunities and instruction are balanced, sex differences either diminish or remain absent, highlighting the importance of early educational interventions aimed at fostering spatial reasoning in both sexes.

Studies have also explored the embodied dimension of MR performance. Jansen et al. (2015) found that in fourth graders, MR performance was more strongly predicted by manual dexterity and the stereotyped nature of the action-based items than by gender itself, with motor skills more closely linked to MR accuracy among boys. This aligns with embodied cognition theories proposing that sensorimotor experiences, such as manual exploration, contribute crucially to the development of spatial transformation ability, potentially in sex-differentiated ways.

Overall, current evidence suggests that sex differences in preschool MR performance are minimal or context-dependent, shaped by complex interactions among neural maturation, psycho-social beliefs, and experiential factors. As research continues, interventions emphasising spatial play, parent engagement, and stereotype-challenging environments may be critical in promoting equitable development of spatial skills and narrowing later gender gaps in STEM participation (Kung & Hines, 2025; Levine et al., 2016). Although sex differences in spatial cognition are robust in adults (Linn & Petersen, 1985; Voyer et al., 2000) but Terlecki and Newcombe (2005), evidenced that such differences may be mediated by differential digital experience and their early emergence remains inconsistent. As both earlier (Caldwell & Hall, 1970; Jahoda, 1979; Kaess, 1971) and more recent (Estes, 1998; Frick et al., 2009; Kosslyn et al., 1990; Krüger & Krist, 2009; Levine et al., 1999; Platt & Cohen, 1981) findings reveal, consistent evidence for a male MR advantage does not typically appear in all preschooler samples, emphasizing the importance of more longitudinal (Lauer et al., 2019), context-sensitive research to uncover how these differences unfold across development.

1.3.3 Link Between Motor Skills and MR in Preschoolers

Inevitably, understanding the role of motor skills in the development of MR during the preschool years is critically important, given that this developmental stage involves substantial advancements in both fine and gross motor functions. Unlike infancy, characterised by rapid and easily observable motor milestones, motor development during the preschool period progresses more gradually, rendering its influence on cognitive processes less immediately apparent. Due to this, the amount of focused research on the link between motor skills and MR is relatively scarce.

Nevertheless, motor influences on MR in preschoolers have only been addressed in a couple of experiments. In one of these experiments, the interference between motor processes and MR, as in adults (Wexler et al., 1998; Wohlschläger & Wohlschläger, 1998), was observed in children. Frick et al. (2009) asked 5-year-olds, 8-year-olds, 11-year-olds, and adults to judge whether 2D jigsaw puzzle pieces matched a notch below. These pieces were presented at different angles; hence, it was expected that the participants would perform MR to assess whether the pieces were potential mates for the notches. This assumption was confirmed, as the RTs increased with the angle of rotation. While working on these tasks, participants had to spin a hand crank. It turned out that the 5-year-olds and the 8-year-olds made their decisions faster when the spinning of the wheel matched the assumed path of the MR rather than the other way round. This effect did not occur in the 11-year-olds or the adults. This result suggests a stronger link between imagery and motor processes in younger children, but it might also result from a lack of sufficient task demand for the older participants.

In a further developmental study, Funk et al. (2005) confirmed Parsons (1987, 1994) findings: 6-year-old children, when asked to identify rotated pictures of left and right hands, showed the expected pattern of being able to answer faster when the posture of their own hand matched that of the displayed hand. For example, when their own hands were placed palms down on the keyboard, they were faster at identifying hands shown from a dorsal perspective (i.e., palms averted) than from a palmar perspective (i.e., palms up) and vice versa. Funk et al. (2005) also found that the RTs tended to depend on the hypothetical movement required to bring the hands into the displayed position. As these effects were stronger in children than in adults, the authors concluded that the connection between motor and imagery processes was also stronger in children than in adults. Sekiyama et al. (2014) adopted a related but more quantitative approach. In their study, younger children (especially 6-year-olds) were unable to keep their hands still and were excluded from analysis. Among the remaining participants, the influence of motor constraints on mental hand transformations systematically declined with age: it was strongest in 7-year-olds, weaker in 8- and 9-year-olds, and minimal in 10-year-olds and adults. They proposed a developmental sequence in which young children rely on overt motor actions, older children on motor imagery, and adults on more abstract visuomotor imagery. Both these studies, align with a Piagetian perspective, suggesting that imagery and other higher cognitive functions originate from sensorimotor processes. As cognitive development progresses, reliance on embodied motor processes decreases, allowing for more flexible and abstract forms of thought. Consequently, younger children should exhibit stronger embodiment effects than older children and adults. In contrast, strong embodiment theories reject this developmental emancipation from motor processes. They propose that motor imagery and motor control are functionally identical and form the foundation of all imagery processes (Prinz, 1990).

Building on the embodiment findings, Krüger and Ebersbach (2018) tested kindergartners and first-graders on an MR task adapted from an adult version Krüger et al. (2014a), in which they were asked to rotate cube configurations that either included human body parts attached in anatomically possible or impossible ways, or consisted solely of cubes. Despite the task not being simplified for children, all participants performed above chance level. First-graders responded faster and more accurately than kindergartners, indicating measurable developmental progress. Across both age groups, clear embodiment effects emerged: children performed better with anatomically possible configurations and worse with anatomically impossible ones compared to pure cube stimuli, revealing both facilitative and inflexible aspects of embodiment. No qualitative age-related differences were observed, suggesting that the nature of embodiment remains stable across early childhood. These results mirror findings from adults and align with the Piagetian view that mental imagery is grounded in early sensorimotor processes. Contrary to theories proposing an increasing integration of motor control and imagery with age, the comparable embodiment effects in children and adults suggest that imagery remains rooted in sensorimotor mechanisms throughout development.

Frick et al. (2013a) advanced this line of research by developing a child-centric touchscreen MR paradigm specifically designed for preschool children aged 3½ to 5½ years. In this task, children were presented with figures or their mirror images at various angular disparities and asked to identify the correct aperture through which the figure would fit. The study revealed a marked developmental trajectory: 4-year-olds' performance remained at chance regardless of angular disparity, indicating limited MR ability at this age, while 5-year-olds exhibited classic MR signatures, including increased error rates and response times corresponding to larger angular disparities. This pattern suggests that MR processes become systematically more engaged with age. Crucially, the study demonstrated that embodied experiences significantly modulated MR performance. Both manual (hands-on practice) and observational training (where an experimenter turned the stimuli) led to improvements in spatial accuracy, but these benefits were primarily restricted to the older preschoolers. These findings highlight the interplay between cognitive maturation and embodied motor experiences in fostering the development of MR during early childhood.

Complementing this, Jansen and Heil (2010) measured both gross and fine motor abilities by using a standardised motor test (MOT 4-6; Zimmer and Volkamer (1987) and investigated the link with MR abilities in preschool children. Their results revealed significant positive correlations between body coordination and agility with 2D-MR performance, suggesting that motor coordination supports the cognitive mechanisms required for mental spatial manipulations. Further research highlights the complex interplay between motor skills, working memory, and MR performance in children. Lehmann et al. (2014) demonstrated that working memory capacity significantly influences MR abilities in young children aged 3 to 6 years. Their study found positive correlations between children's spatial working memory, which was measured through tasks such as the Corsi Block Tapping Test (Kaufmann et al., 2008), and MR performance, indicating that efficient working memory supports the encoding, maintenance, and manipulation of spatial representations required for MR tasks. This relationship suggests that developmental improvements in working memory contribute to enhanced MR capabilities during early childhood. Further, quasi-experimental studies have revealed that impaired motor performance is associated with deficits in MR. For instance, Jansen et al. (2011b) reported that children with obesity often exhibit poorer motor skills alongside lower MR performance, suggesting that reduced motor competency may adversely affect spatial cognition. Similarly, Wiedenbauer et al. (2007) found that children with spina bifida demonstrate both motor impairments and significant difficulties in MR tasks, reinforcing the notion that motor abilities and spatial cognitive functions are interconnected.

Expanding the understanding of motor-based interventions on MR, Wiedenbauer and Jansen-Osmann (2008) designed a manual rotation training program to investigate its influence on MR abilities in older children (ages 10-11). The training involved participants rotating stimulus pairs using a joystick, aligning one image to an upright orientation relative to another. Over a 60-minute session that included pre- and post-testing with a chronometric MR task, the study found significant improvements in MR performance attributable to manual rotation practice. Importantly, children in the experimental group showed faster MR speeds post-training and transfer of training effects to novel stimuli not used during the intervention. This indicates not only enhancement of MR accuracy but acceleration of underlying cognitive rotation processes. The ability of manual rotation training to generalise beyond practised stimuli underscores its potential as an effective method to strengthen fundamental spatial cognitive skills in children, with implications for both educational practice and cognitive development theories. Blüchel et al. (2013) examined the impact of motor training on MR performance in children aged 8 to 10 years. Two groups of children, completed a psychometric MR task involving 3D block figures. Following the initial assessment, one group underwent a two-week coordinative motor training program, performed daily for 20 minutes during the school day, while the control group received no additional training. After the training period, all participants repeated the MR task. Both groups showed significant improvement from pre- to post-test; however, the motor training group demonstrated a substantially greater increase in MR performance compared to the control group. Jansen et al. (2011a) conducted a study with girls aged 6–14 years to examine the impact of juggling on MR. Participants completed a computerised MR task with 3D block figures before and after the intervention. The findings indicated that children in the juggling group demonstrated significantly faster RT at non-zero angular disparities compared to those in the control group. This further strengthens the premise that there is an association between MR ability and motor activities. These findings provide empirical evidence supporting the positive influence of targeted motor training on the enhancement of spatial cognitive abilities such as MR, highlighting the importance of embodied motor experience in the development of MR skills during late childhood. Additional intervention research highlights the benefits of play-based motor activities for spatial cognition. Weber et al. (2024) observed that structured block play enhanced MR skills among preschool boys and girls alike. Such activities promote fine motor dexterity, visual-motor integration, and embodied exploration, all of which contribute to the cognitive flexibility required for MR. Fine motor skills, integral to precise object manipulation, have also been linked to superior MR performance. Piek et al. (2008) found that children with enhanced fine motor dexterity, such as better control during drawing or playing with small blocks, demonstrated stronger spatial abilities, including MR. Such skills enable active and detailed engagement with spatial objects, enhancing children's mental simulations of rotations and transformations.

Functional neuroimaging studies reinforce behavioural data by demonstrating overlapping neural substrates for motor control and spatial cognition in early childhood. Hahn et al. (2010) identified activation of parietal and premotor cortices when preschoolers engaged in MR tasks, brain regions traditionally implicated in the integration of sensory-motor information and spatial processing. This neural overlap substantiates the embodied cognition framework, emphasising that spatial reasoning is deeply interwoven with motor experiences (Wu et al., 2020) further highlighted the involvement of the premotor/supplementary motor cortex and the dorsolateral prefrontal cortex, which underpin both hand movement and cognitive control, suggesting that neural mechanisms supporting motor function are integral to successful MR even in young children.

Overall, current research adopting longitudinal and experimental designs to clarify the relationship between motor skill development and MR performance are scarce. Specifically, studies should distinguish the unique contributions of fine and gross motor skills across developmental stages to determine how each supports different aspects of spatial cognition. Expanding current paradigms to include more complex 3D rotation tasks would also help capture the progression from embodied, action-based strategies to more abstract visuo-spatial processing.

1.4 Research Gaps and Aims

Building on the preceding sections and the current state of the literature, several research gaps and open questions have been identified, which will be addressed in this section.

1.4.1 3D-MR Development

To encode and memorise an object, one must process information about distance (or length), angle, and direction (or sense: left vs right). Because such cues are specified in relation to a particular point of origin or a chosen frame of reference, spatial cognition is relational in nature. For instance, determining the shape of a cube involves reasoning about angles and relative side lengths; locating it within a large-scale environment involves reasoning about distances and directions, which can be determined either relative to a stable reference point or relative to an individual moving through that environment. Although previous research has demonstrated that infants show signs of MR, studies differ widely in the types of stimuli (2D or 3D) and methods used across age groups. Classic adult MR tasks, such as those developed by Vandenberg and Kuse (1978), employ 3D Shepard Metzler objects rotated in depth but presented as static 2D images. In contrast, infant studies typically rely on looking-time measures that infer MR from novelty or familiarity preferences. However, such paradigms differ markedly in the perceptual demands and dynamics of the stimuli used. For instance, Quinn and Liben (2008) employed static images within habituation tasks, whereas Schwarzer et al. (2013b) presented dynamically rotating 3D objects. Despite their methodological differences, both studies provided evidence that infants can mentally track object rotations. At the preschool level, MR tasks often require overt responses such as selecting identical or mirror-reversed objects. Even at this stage, most studies continue to employ static or 2D stimuli (Hoyek et al., 2012), and very few studies, such as Hawes et al. (2015a), examined 3D-MR in preschoolers. Yet, critical questions about how MR competence develops across dimensional contexts remain open (Bruce & Hawes, 2015).

There are only a few studies which have shed light on this issue. For instance, in a training study, Wang et al. (2020) demonstrated that targeted spatial training improved 3D-MR, indicating that this skill set is both distinct from and more flexible than its 2D counterpart. Münzer (2015) advanced this line of inquiry by showing that animated 3D stimuli facilitate better MR performance than static images, suggesting that dynamic visualisation supports spatial transformation by providing perceptual continuity. Similar findings have been reported in infancy research: Soska et al. (2010) showed that infants can complete partially occluded 3D objects and display a preference for novel views, implying early object constancy and foundational MR abilities. Moreover, infants tend to interact longer with physically present 3D objects than with flat 2D representations, suggesting that different cognitive mechanisms may be engaged depending on dimensionality. Additionally, a study by Courbois (2000) used unfamiliar stimuli with or without a salient intrinsic axis to test 5- and 8-year-olds' MR performance. Both age groups succeeded when stimuli contained a clear axis, but 5-year-olds struggled with axis-ambiguous shapes, suggesting that the ability to encode and manipulate orientation-ambiguous forms develops substantially between early and middle childhood. Such findings align with the broader view that perceptual structure and object encoding critically constrain MR efficiency during development.

Investigating 3D-MR development poses substantial methodological challenges. Tasks must be engaging, cognitively accessible, and age-appropriate, enabling children to encode, recognise, and mentally transform objects. Empirical evidence consistently shows that 3D-MR is cognitively more demanding than 2D-MR because it requires reconstructing unseen object views Jolicœur et al. (1985). For example, rotating a picture of a car within the same plane preserves visual features, whereas imagining its rear view after seeing only the front in 3D space requires mental reconstruction of hidden surfaces and spatial reorientation, imposing greater cognitive load.

Additionally, a core methodological feature of MR is the effect of angular disparity. Yet it remains particularly underexplored in early development. Gerhard and Schwarzer (2018) work demonstrated that infants could discriminate 3D objects rotated by 90 degrees, but comparable studies using 3D objects in preschool-aged children are nearly absent. Establishing whether preschoolers' 3D-MR performance varies with angular disparity would provide critical evidence for the emergence of adult-like MR processes and clarify how sensitivity to angular variation develops with age. Examining angular disparity in 3D space introduces additional perceptual demands, particularly when depth rotation is involved, as occlusion and perspective reconstruction increase cognitive complexity.

Taken together, these studies point toward a potential need to elucidate 3D-MR processing, especially in preschoolers using cross-sectional designs. Furthermore, to date, no known study has systematically investigated 3D-MR development at both infancy and preschool ages. Understanding whether early MR abilities, as observed in infancy, predict later 3D-MR competence would provide crucial insight into the developmental continuity of spatial cognition.

1.4.2 Lack of Longitudinal Studies on 3D-MR

Apart from the longitudinal study by Lauer and Lourenco (2016), there is no existing evidence tracing the development of MR from infancy to preschool age. In particular, no study to date has tracked how MR with 3D objects develops across these formative years. Following 3D-MR longitudinally presents substantial methodological and measurement challenges. Tasks designed for infants, such as looking-time or violation-of-expectation paradigms, are nonverbal and rely on indirect indices of cognitive processing, whereas tasks suitable for older children typically involve verbal instructions, overt motor responses, or symbolic reasoning. This difference in measurement method, complicates efforts to investigate developmental continuity in MR competence over time.

Recent methodological advances have begun to address these limitations. Adaptive eye-tracking paradigms provide comparable quantitative metrics across pre-verbal and verbal stages, allowing researchers to examine MR more consistently across early development. However, standardised and validated measures that span infancy through middle childhood are still lacking, leaving the developmental trajectory of MR only partially understood.

A notable step toward bridging this gap was made by Beckner et al. (2023a), who introduced an adaptive eye-tracking procedure incorporating a staircase design to assess MR across early ages. In their study of 12-, 24-, and 36-month-old children, each session began with a short training phase in which children learned to fixate on one of two locations based on a giraffe's orientation (left or right). During the test phase, a two-up, one-down staircase procedure systematically varied the rotation angle of the stimuli, increasing by 30° or decreasing by 15° depending on the child's accuracy. This adaptive approach captured fine-grained, age-related differences in MR performance: accuracy decreased as angular disparity increased, and older children succeeded at larger rotation angles than younger ones. The paradigm represents an important methodological advance, providing a developmentally sensitive and functionally equivalent tool for assessing MR across a continuous age range. However, this method does not cover younger infants.

While considerable research has examined MR across different ages, most studies remain cross-sectional, comparing separate groups at single time points. Although such work offers valuable age-based insights, it cannot capture the intra-individual processes through which MR emerges and evolves. Longitudinal approaches, in contrast, track the same individuals over time and are uniquely positioned to reveal the dynamic mechanisms of spatial-cognitive development. Yet applying this approach to 3D-MR research remains complex, requiring age-calibrated, attention-sustaining tasks that minimise floor and ceiling effects while maintaining comparability across multiple developmental stages.

1.4.3 Role of Motor Development in 3D-MR

Examining the relationship between motor development and 3D-MR becomes especially important. Empirical studies in infancy lend initial support to this motor–MR connection. Research by Gerhard-Samunda et al. (2021), Kelch et al. (2021), and Schwarzer et al. (2013b, 2022) has consistently shown associations between motor development and MR performance when 3D stimuli are used, suggesting that the ability to interact with and manipulate objects in space facilitates mental transformations of those same objects. Despite these promising findings in infancy, comparable evidence during the preschool period remains limited. Most MR studies with preschoolers rely on static or 2D stimuli and do not incorporate measures of motor development. For instance, Jansen and Heil (2010) used the 2D Picture Rotation task (Quaiser-Pohl, 2003) to measure MR and evidence a link between 2D-MR and motor control. To date, no study has systematically linked children's motor abilities with MR performance using 3D objects that vary in angular disparity. Consequently, it remains unclear whether the motor–MR link observed in infancy extends into preschool age when MR becomes more explicit and cognitively demanding. Furthermore, whether early motor achievements, particularly self-produced locomotion, predict later 3D-MR competence has not yet been explored. Longitudinal research tracking the developmental interplay between motor skills and 3D-MR from infancy to preschool would therefore provide essential insight into how embodied action shapes the maturation of spatial cognition.

1.4.4 Linking Prediction and MR Abilities

Despite this growing evidence on MR, several questions remain unresolved. One central issue is whether intra-object processing is related to inter-object processing in infancy. Addressing this gap is crucial for understanding how different components of spatial cognition interact during infancy. Building on Piaget's notion of object permanence, the understanding that objects continue to exist when out of sight, linking predictive tracking with MR could illuminate how infants integrate dynamic information about both object constancy and transformation. In the previous sections, it is seen that there is much research on MR and predictive gaze separately; however, no one has linked it together in infant literature. For instance, Kubicek et al. (2017b) reported associations between prediction rates and motor skills, while Gerhard-Samunda et al. (2021) found similar links between MR and motor abilities. However, to date, there is no clear evidence showing how MR and anticipation tasks are directly related, nor whether they rely on similar underlying mechanisms. In older children, MR has been associated with perspective-taking, a skill that shares conceptual similarities with predictive reasoning. Additionally, the eye tracking task discussed by Pedrett et al. (2020) shows how the rotational movement in the eye tracking task and the predictive gazes and the looking times in the same task do not correlate. However, this could be because the task was employed on older children, who have higher cognitive demands, and we cannot rely too much on looking time measures. It is plausible that the link between the MR and predictive abilities might emerge differently in infancy. Interestingly, it would also be intriguing to see how motor skills shape both these processes in the same individual. Yet, much less is known about how these processes are connected during infancy, when the foundational elements of spatial cognition are still emerging.

1.5 Objectives of the Present Work

This dissertation aims to fill these four abovementioned critical gaps in the developmental literature by (i) characterising the developmental trajectory of 3D-MR from infancy through the preschool years, (ii) identifying the key factors that drive 3D-MR development, particularly self-produced locomotion and broader motor skills, and (iii) examining the relationship between 3D-MR and prediction ability, which are foundational to spatial cognition. Previous research has primarily examined the emergence of MR either in infancy or early childhood, leaving the developmental continuity of 3D-MR across these stages insufficiently understood. Focusing on children aged 9 months to 6 years provides a unified perspective across two pivotal developmental periods: infancy and early childhood.

The present work adopts a developmental psychological framework that uses both longitudinal and cross-sectional approaches to capture developmental change and individual variability. It incorporates age-appropriate experimental tasks to assess 3D-MR and simultaneously evaluates influential factors such as motor development. Crucially, in contrast to the prevailing reliance on 2D stimuli in prior research, the present dissertation exclusively uses 3D stimuli across all studies. Grounded in theories of embodied cognition and developmental systems, this dissertation aims to uncover whether self-produced locomotion and manual exploration contribute to the formation and refinement of 3D object representations in early life.

Specifically, the scientific objectives of the dissertation are addressed through three empirical studies:

Study 1 characterises the longitudinal developmental course of 3D-MR from infancy to preschool age, along with the potential role of motor skills. By employing comparable 3D-MR tasks across, this study focuses on identifying whether infants' ability to mentally transform 3D objects is related to 3D-MR skills during the preschool years. Building on the premise that perception and action are tightly coupled, this research examines whether early motor milestones, particularly crawling ability and the concurrent motor abilities, are related to 3D-MR at both developmental stages.

Study 2 explores the association between 3D-MR and motor skills (both fine and gross) in preschoolers. Through a cross-sectional design involving younger and older preschoolers, this study employs a novel block task to measure 3D-MR. Particularly, this study aims to investigate to see whether the link found between 3D-MR and motor skills in infancy persists in preschool age.

Study 3 examines the relationship between intra-object and inter-object spatial processing during infancy. A novel contribution of this work is the empirical investigation of whether 3D-MR (intra-object processing) and visual prediction (inter-object processing) are linked, along with motor abilities contributing to their development. Using 3D stimuli and eye-tracking technique, the study assesses whether infants who can anticipate the movement or reappearance of objects also demonstrate enhanced ability to mentally rotate, and whether these relations are modulated by locomotor experience.

Collectively, through these objectives, the present work aims to provide a comprehensive, empirically grounded account of the development of 3D-MR and the factors that influence it across early childhood. Beyond its theoretical implications, the research offers practical insights into how early motor experiences may scaffold later spatial reasoning, informing educational strategies and early interventions aimed at fostering the visuospatial skills that underpin mathematical, scientific, and everyday problem-solving competence.

Chapter 2

Role of Motor Skills in the Development of Mental Rotation from Infancy to Preschool Age: A Longitudinal Study (Study 1)

Note: A version of this chapter has been submitted for publication in *Acta Psychologica* and is currently under review.

2.1 Background

Building on the crucial research gaps outlined in the previous chapter, Study 1 aims to highlight the development of 3D-MR from infancy to preschool age. Two central lines of previous findings motivate this study. First, given that our environment is inherently 3D, and infants demonstrate a preference for 3D objects over 2D representations (Gerhard et al., 2016), it is essential to assess MR using age-appropriate 3D tasks at both time points. As reviewed in Chapter 1, 2D and 3D-MR abilities in infancy are measured using looking–time–based paradigms, such as habituation (Quinn & Liben, 2008, 2014), VoE (Hespos & Rochat, 1997; Rochat & Hespos, 1996), change detection paradigms (Beckner et al., 2023a; Lauer et al., 2015) and eye tracking measures (Beckner et al., 2023b), while in MR tasks in preschoolers are based on different task formats, such as same-different judgments (Krüger et al., 2014a) and forced-choice paradigms (Fernández-Méndez et al., 2020; Frick et al., 2013b), which typically measure error rates and RT. As a result, it remains unclear how infant MR is related to preschool MR, especially due to the various methodological differences employed at each time point. One of the fundamental conundrums while examining the developmental trajectory of MR is to elucidate this developmental transition using similar task formats. Longitudinal studies employing age-appropriate tasks are essential as they allow researchers to determine intra-individual differences in performance at infancy in relation to the corresponding performance at preschool age. Designing age-comparable tasks that accommodate developmental changes and effectively assess MR ability within a targeted age group requires considerable effort and ingenuity. Therefore, a study design which allows for answering the above aspects of the connection between infant and preschooler MR abilities is a longitudinal study with these two time points using age-comparable versions of the same MR task. To date, there is only one longitudinal study with infants and preschoolers on spatial transformation conducted by Lauer and Lourenco (2016). However, the authors did not use age-comparable tasks but two different tasks in 6-month-old infants and 4-year-olds. The infants were tested with a spatial change detection task with stimuli rotated across the picture plane, while the 4-year-olds were tested with the Children's Mental Transformation Test (CMTT) developed by Levine et al. (1999), along with a series of tests for mathematical aptitude. The two spatial transformation tests used at the two time points did not show any overlap concerning the stimuli used or the requirements of the tasks. Interestingly, the authors did find a high correlation of r = .47 between infants' spatial performance and 4-year-olds' mental transformation abilities. This suggests that infants' performances in the change detection task significantly predicted their mental transformation abilities at 4 years of age. However, both tasks were 2D in nature. There is still no study on 3D-MR at both these time points.

Second, previous findings have also indicated that motor skills like crawling drive MR during infancy. Using a habituation paradigm with a rotating 3D Shepard-Metzler object, Schwarzer et al. (2013b) demonstrated that 9-month-old crawling infants showed a novelty preference towards the mirrored object, indicating MR ability, while non-crawlers did not. Gerhard-Samunda et al. (2021) further emphasised that crawling is associated with more differentiated processing of self-generated rotation-specific visual cues, thereby improving 3D-MR performance. The causal link between locomotion and 3D-MR was further confirmed by Schwarzer et al. (2022), who found that compared to infants without self-produced motor experience, pre-locomotor infants trained to locomote showed a significantly higher ability to differentiate between habituation and mirror objects. These findings support the idea that self-produced locomotion, like crawling, drives the development of MR in infancy. They also raise the question of whether this advantage in 3D-MR for crawling over non-crawling infants still persists at preschool age and whether the 3D-MR performance of preschoolers is connected to their current motor skills. To date, there are no studies investigating whether the advantage of 3D-MR in crawling infants remains at preschool age. Jansen and Heil (2010) showed that 2D-MR is linked to motor agility and coordination in preschoolers; however, it is unclear if this link persists with 3D stimuli in preschoolers.

2.2 Objectives

Building on the promising results of Lauer and Lourenco (2016), Study 1 aims to investigate the link between infants' and preschoolers' MR abilities using age-comparable tasks that explicitly involve rotation across depth. Specifically, we sought to examine whether a stronger correlation would emerge when using age-comparable MR tasks, in contrast to the heterogeneous ones used by Lauer and Lourenco (2016). Creating tasks that account for developmental differences and accurately evaluate MR ability, while using similar stimuli in both age groups demands significant creativity and effort (Beckner et al., 2023a; Pedrett et al., 2023; Stark et al., 2024). One approach to resolve this issue is to develop a new measure capable of assessing MR for a broader age range, from infancy to early childhood. For instance, Beckner et al. (2023a) devised a novel staircase eye-tracking paradigm to evaluate MR in children aged 12 to 36 months. However, it remains unclear whether such paradigms can be effectively employed with older preschool-aged children. In the present study, our goal was to create an MR task for preschoolers that closely resembles the previously used infant MR task Gerhard-Samunda et al. (2021). To ensure methodological consistency, both tasks utilised 3D Shepard-Metzler objects, and both were based on the same conceptual framework, namely, distinguishing between a target object and its mirror image rotated across the depth plane. To further probe MR processes in preschoolers, we systematically varied the rotational angle of the stimuli, which is a hallmark indicator of MR observed in preschoolers and adults. This methodological refinement extends Lauer and Lourenco (2016) focus on 2D spatial transformations to the domain of 3D-MR, providing novel insights into how infants' and preschoolers' abilities to mentally manipulate objects in depth are related longitudinally. Additionally, given prior evidence showing that motor development, such as crawling, is associated with enhanced MR in infancy, as well as studies suggesting associations between motor skills and MR during the preschool years, we included measures of motor skills at both time points as an exploratory aspect of the study. Therefore, a longitudinal study design was adopted to track the development of MR in crawling and non-crawling infants at two distinct test points, 9 months and 4 to 6 years of age, using age-appropriate 3D-MR tasks.

2.3 Methods

2.3.1 Sample

This study was conducted in accordance with the German Psychological Society (DGPs) research ethics guidelines. The Office of Research Ethics at Justus Liebig University Giessen approved the experimental procedure and the informed consent protocol. Written informed consent was obtained from the parents of the children before study participation.

For the first test point (T1), we used datasets from the MR infant study by Gerhard-Samunda et al. (2021). The original sample included 43 healthy, full-term 9-month-old infants (27 males; M = 9 months 14 days; SD = 8 days). Infants were recruited by obtaining their birth records from local municipal councils and neighbouring communities. Participants were predominantly Caucasian and lived in urban and suburban areas of Giessen. These infants were recontacted for the second test point (T2) when their ages ranged from 4 years 6 months to 6 years 8 months (preschool age). We experienced dropout due to (i) loss of contact information, (ii) change of address, (iii) lack of interest, and (iv) scheduling conflicts. Thus, at T2 (preschool age), our final sample consisted of 24 children (14 males; *M* = 5 years 8 months, *SD* = 6 months). Of these participants, 13 were crawlers, and 11 were non-crawlers during infancy (*M*= 9 months 4 days, *SD* = 9 days). The crawling status was calculated using a movement calendar to interview the parents about infants' motor behaviour (see Schwarzer et al. (2013a) for more detail). Infants who were able to crawl on hands and knees for at least 2 weeks were categorised as crawlers.

For T2, power analysis indicated that our sample size (n = 24) provided adequate power $r(1-\beta) > 0.80$, $\rho_s \geq 0.55$ two-tailed) to detect the hypothesised longitudinal correlations between MR performance in infancy and at preschool age. The longitudinal link was estimated by prior research, especially the study by Lauer and Lourenco (2016), suggesting relatively large correlations among the administered mental transformation measures.

2.3.2 Tasks at First Test Point (T1): Infancy

In the study by Gerhard-Samunda et al. (2021), infants first participated in a brief visual cue task followed by the main task, the MR task, which produced the data that was used for the T1 of our study.

Stimuli

The visual cue task consisted of a cylinder (13.3 cm high and 11.5 cm in diameter) with alternating red and blue stripes, oriented either vertically or horizontally (2.0 cm or 1.9 cm in width, respectively), similar to Antrilli and Wang (2016). The MR task was designed according to Moore and Johnson (2008), consisting of two 3-D digitised models of Shepard-Metzler objects (Schwarzer et al., 2013a), an L-object and an R-object, which were created using Blender 2.79 (Blender Online Community, 2017). These objects were mirror images of each other. The L-object featured different colours on its faces: medium red (front), dark red (back), orange (above), yellow (below), pink (left), and ochre (right). Two habituation videos and two test videos (one for each object) were created. Each video showed the object rotating around its vertical axis at 48° per second. Habituation videos displayed rotation from 0° to 239°, with the object reversing its direction after reaching the maximum rotation. Test videos depicted rotation from 240° to 359° (see Figure 2.1).

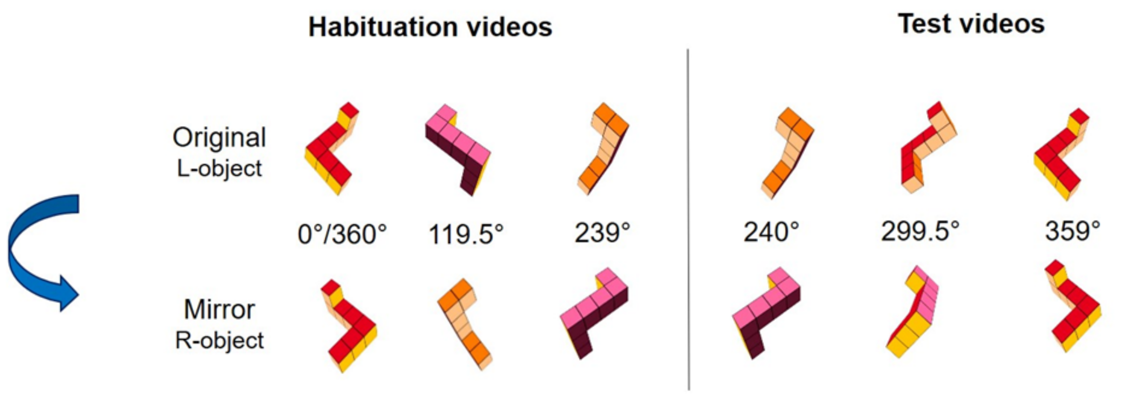

Figure 2.1: Infant MR habituation task. The L-object is shown at the top, and the R-object at the bottom. Both objects are mirror images of each other. In the habituation videos, the objects rotated back and forth between 0° and 239°. In the test videos, the objects rotated back and forth through the previously unseen angle, from 240° to 359°.

Procedure

Infants first participated in the visual cue task, where they were instructed to spin the cylinder. This resulted in rich visual rotation cues for the vertically striped cylinder and minimal visual rotation cues for the horizontally striped cylinder. This was followed by the MR task, where an infant-controlled habituation phase was followed by a test phase. Infants were randomly assigned to view either the L- or R-habituation video in the habituation phase. The habituation phase ended when infants habituated to the habituation video within 12 trials or when fixation time dropped to 50% of the average time within the first three trials. After habituation, six test trials were conducted, alternating between the videos of the habituation object and the mirror object, each presenting the previously unseen arc. The first trial of the test phase was also counterbalanced across all participants. Fixation times were coded for all the trials using the Habit X 1.0 (Oakes et al., 2019) software.

2.3.3 Tasks at Second Test Point (T2): Preschool Age

At T2, children participated in an age-adjusted MR task, which was similar to that of the infant MR task. To validate this new age-adjusted task, children completed a standardised German MR test, the Bilder Rotations Test (BiRT) developed by Quaiser-Pohl (2003). To control for intelligence, they also participated in a general intelligence test, the Coloured Progressive Matrices (Raven, 2003; Raven et al., 2002). They also did the Leistungsinventar zur objektiven Überprüfung der Motorik von 3-bis 6-Jährigen (LoMo 3-6 version B assesment) developed by Jaščenoka and Petermann (2018) .

Bilder Rotation Test (BiRT)

Children first completed the German version of the Picture Rotation Test called the Bilder Rotation Test (BiRT), developed by Quaiser-Pohl (2003), which is a standardised German paper-and-pencil-based MR test. There are 16 items in total. Each item contains four pictures, one target image on the left side and three repeated pictures on the right side rotated at 45°, 90°, 135°, or 180° relative to the target object. One of these three comparison pictures is identical to the left picture; the other two are mirror images of the target (see Fig. 2.2 for item examples). The children were asked to point at one of the three rotated pictures, which they thought was identical to the target picture. The maximum score was 16, and the split-half reliability is 0.74.

Figure 2.2: Example of a child performing the BiRT. The test item is rotated at 45°, and the child is asked to point to the correct option out of three that matches the target on the left. The correct answer is the first option. Item is from Quaiser-Pohl et al. (2003) test manual.

Age-Adjusted MR Task

Stimuli

Familiarisation Video: Comparable to the infant MR task, we generated a video of the simplified Shepard-Metzler R-object rotating from 0° to 360° while maintaining consistency with the infant videos in terms of speed, rotation axis, and colour. Using this video, we created a familiarisation video that rotated from 0° to 119° (Fig.2.3). Upon reaching 119°, the object reversed its direction, rotating back to 0°. This video was mirrored to create the video of the L-object while preserving the same movement dynamics.

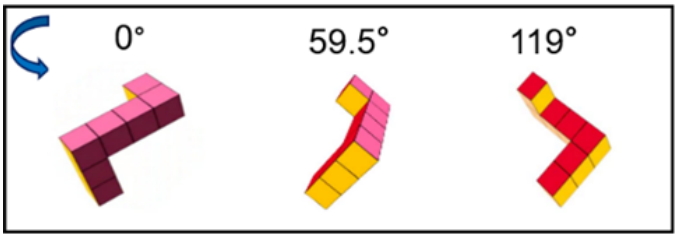

Figure 2.3: T2 Age-adjusted MR Task video. Representation of the rotating video from 0° to 119°

Test Images: Static images were extracted from the remaining segment of the R-object video (120° to 359°) with an interval of 59.75°, resulting in five different angles: 120°, 179.75°, 239.5°, 299.25°, and 359°. These images were mirrored to produce the corresponding L-object images. Each static image of the R-object was paired with its counterpart L-object image (Fig.2.4).

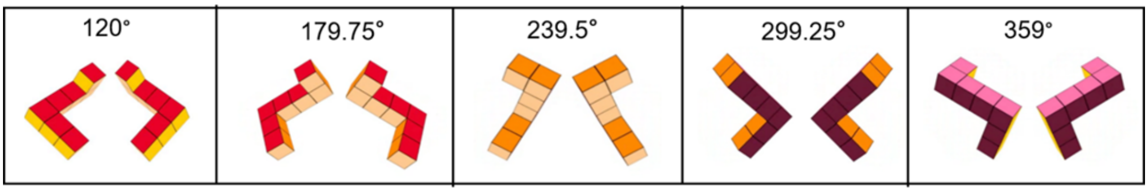

Figure 2.4: T2 Age-adjusted MR Task static images. Representation of the pairs of static images presented in five different angular disparities ranging from 120° to 359° with an interval of 59.75°.

Creation of Test Trials: Each test trial featured a familiarisation video on the left side of the screen and one of the five pairs of static images (L-object and R-object) on the right (Fig.2.5). A black line separated the familiarisation video and pairs of images. Children viewed either the L- or R-object familiarisation video with the corresponding static images, with each pair shown twice, totalling 10 trials. The position of the image corresponding to the video object was counterbalanced to prevent side bias (see randomisation plan in Appendix 6).

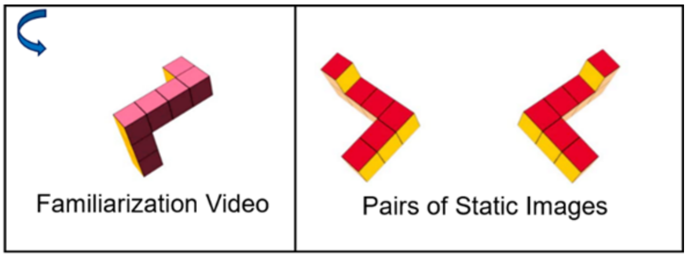

Figure 2.5: T2 Age-adjusted MR Task trial. Representation of a trial with a video rotating back and forth on the left and a pair of static images (here, a 120° trial) in the middle and right. Each angle was presented twice in two different trials: one trial included feedback and the other was without feedback, for a total of 10 test trials.

Feedback Videos: For providing feedback about their responses, rotated the familiarisation videos until it reaches the angle of the static image presented. Hence, the feedback videos ranged from the start of the rotating L-or R-object video to the respective static image. This resulted in five feedback videos, covering the ranges from 0° to 120°, 0° to 179.75°, 0° to 239.5°, 0° to 299.25°, and 0° to 359°.

Procedure

The MR task was conducted in a rectangular cabin with an open front, where the child was seated 60 cm from the screen, embedded in the rear wall of the cabin. The MR task was presented using MS PowerPoint (Microsoft, 2016), controlled by an experimenter seated behind the cabin. The experiment began with a blank white screen, followed by a chime sound (an attention-getter) and the 10 test trials.

Practice Trials: The first two test trials featuring static image pairs at 120° and 359°, respectively, served as practice. During these trials, the familiarisation video of the L- or R-object (rotating from 0° to 119°) was shown on the left of the screen for 15 sec, displaying three rotations back and forth. Children were instructed to carefully observe the object's shape and form. Subsequently, another chime sound signalled the start of the test trial by presenting the static images, where the child was asked to point at the object image, which matched the object from the video. Both the video and the images remained on the screen until the child responded. Visual feedback was provided by highlighting the correct static image and showing the continued rotation of the image in the feedback video, accompanied by verbal feedback. The verbal feedback was consistent for all the children, wherein they were explained why it was the correct object.

Test Trials with Feedback: Trials 3 to 5 featured videos and the static images at angles of 299.25°, 179.75°, and 239.5°, respectively. Each trial was followed by only visual feedback about the correct object and by demonstrating why the object was correct via the corresponding feedback video.

Test Trials without Feedback: Trials 6 to 10 included video and static image pairs at angles 120°, 299.25°, 179.75°, 239.5°, and 359°, respectively. These trials did not include any visual feedback.

Intelligence Test

We utilised the *Coloured Progressive Matrices* (CPM) developed by Raven (2003). It is a culture-fair intelligence test. The CPM consists of 36 items arranged in three sets of 12 items each. Each item contains a figure with a missing piece. Below the figure are six alternative pieces to complete the figure, only one of which is correct. Each set involves a different rule for obtaining the missing piece, and within a set, the items are roughly arranged in increasing order of difficulty. Retest reliability reads 0.90, and internal consistency is 0.64 (Schmidtke & Schaller, 1980).

Motor Test

We administered the *Leistungsinventar zur objektiven Überprüfung der Motorik von 3-bis 6-Jährigen* (LoMo 3-6 version B) developed by Jaščenoka and Petermann (2018), which is a standardised German test for measuring fine and gross motor skills from the age of 4.6 to 6.11 years. It consists of 32 items and the total score indicates the level of motor development in the child for various areas of fine motor skills (drawing shapes, finding a way along a line, folding, rotating objects with finger coordinated, threading beads, screwing nut and bolt, finger tapping and foot stomping), body coordination (balancing along a line, standing on one leg, and jumping jacks), strength and endurance (hurdle race, running, prompt stopping, and running under a rope) as well as object control (throwing and catching ball). We evaluated each item by two independent coders and reached a Cronbach's alpha of 0.976.

2.4 Data Coding and Scoring

2.4.1 Infant MR task (T1)

As we used infant data from Gerhard-Samunda et al. (2021) in T1, infants' responses in the MR task varied depending on the experimental condition of the visual task, with some infants showing a novelty preference and others a familiarity preference. To minimise the influence of these condition-specific preference directions, we focused on the magnitude of discrimination rather than its direction. Following Schwarzer et al. (2022) we first averaged infants' looking times separately for each test stimulus, including three trials of the habituation object and three trials of the mirror object presented at previously unseen orientations. We then computed a difference score by subtracting the average looking time to the familiar (habituation) object from the average looking time to the mirror object. A difference score of zero indicates no discrimination between the two stimuli.

Positive values reflect longer looking times to the mirror object, whereas negative values reflect longer looking times to the familiar object. As our focus was on infants' ability to distinguish between the stimuli rather than their preference direction, we used the absolute value of this difference score as an index of discrimination ability. This measure captures infants' ability to differentiate between the familiar object in a novel orientation and its mirror counterpart, representing a fundamental component of MR.

2.4.2 Age-adjusted MR Task (T2)

As children responded by pointing to one of two static images, accuracy data were binary (correct vs. incorrect), and hence each trial was scored as 0 or 1. Practice trials were included in the accuracy calculation for trials with feedback, resulting in five trials with feedback and five trials without feedback. Total accuracy was calculated across all 10 trials, yielding a maximum possible score of 10.

2.4.3 Motor Test (T2)

The LoMo assessment was coded according to the manual guidelines. Each task was scored based on the specified criteria, and a Total LoMo Score was calculated following the standardised procedure described in the manual, consisting of both fine and gross motor skills. Scores ranged from 0 to 74. As the manual applies to children aged 4.6 to 6.5 years and does not require age-specific adjustments within this range, scoring was consistent across participants. Therefore, we used the Total LoMo Score as a measure of motor ability, as it is directly comparable across all children in our sample.

2.5 Results

Statistical analyses were performed using JASP Version 0.18.3 (JASP Team, 2024).

2.5.1 Test Point 1 - MR Performance (Difference Scores) in Infancy

As the difference scores were not normally distributed ($W = 0.87$, $p = .007$), non-parametric tests were used. Infants' difference scores in the MR task were significantly above 0 ($Mdn = 3.61$ sec), indicating their ability to distinguish between the objects, $W = 300$, $p < .001$. Additionally, no sex differences were observed ($U = 56.5$, $r = -.19$, $p = .44$). To assess the impact of the visual cue task, we ran a Mann-Whitney U test, revealing no significant result in the difference scores between the vertical ($Mdn = 3.20$ sec) and horizontal ($Mdn = 4.03$ sec) conditions ($U = 71$, $r = -.007$, $p = 1.00$). As the visual cue task did not affect the results in our sample, we collapsed data across these conditions in the analyses. Furthermore, there was no significant difference between the difference scores of infants who came back for T2 and those who didn't ($U = 224$, $r = -.01$, $p = .93$), indicating that the T2 sample was not biased toward infants with only high or low performance at T1.

A Chi-square test was used to examine the association between crawling status (crawlers vs non-crawlers) and MR performance (high vs low difference scores based on median split). A significant association was found, $\chi^2(1, 24) = 4.19$, $p = .04$, indicating that crawlers demonstrated a higher difference score than non-crawlers. Among the crawlers, 69% ($n = 9$) had high difference scores while 31% ($n = 4$) had low difference scores. In contrast, 73% of the non-crawlers ($n = 8$) had low difference scores, and 27% ($n = 3$) had high difference scores.

2.5.2 Test point 2 - MR Scores (Accuracies) in Preschool Age

MR Task

Accuracy for the age-adjusted MR task was calculated separately per trial, for both trials with feedback (1-5) and trials without feedback (6-10), as well as for the total accuracy across all 10 trials. Normality tests revealed accuracy in trials with feedback ($W(23) = 0.92$, $p = .06$) and across all trials ($W(23) = 0.92$, $p = .07$) followed a normal distribution. However, accuracy in trials without feedback was not normally distributed ($W(23) = 0.91$, $p = .03$). Consequently, we used parametric tests to analyse trials with feedback and overall accuracy, and non-parametric tests were employed for the trials without feedback. Accuracies were significantly above chance in the trials with feedback ($M = 3.20$, $SD = 1.14$), $t(23) = 3.04$, $d = 0.62$, $p = .006$ and in the trials without feedback ($Mdn = 3$), $U = 242.50$, $r = .61$, $p = .007$. The total accuracy across all the trials ($M = 6.45$, $SD = 1.97$) was also above chance, $t(23) = 3.61$, $d = 0.73$, $p = .001$.

A Wilcoxon signed-rank test revealed no significant difference between performance in the trials with feedback ($Mdn = 3$) and the trials without feedback ($Mdn = 3$), $W = 68$, $p = 1.00$.

An independent t-test revealed that girls ($M = 7.50$, $SD = 1.90$, $n = 10$) showed significantly higher accuracy than boys ($M = 5.71$, $SD = 1.73$, $n = 14$) across all the trials of the MR task, $t(22) = -2.39$, $d = -0.99$, $p = .02$. No significant difference in accuracy was found between the R- and L-object versions of the task, $t(22) = -1.75$, $d = -0.73$, $p = .09$. No sex difference was found in trials without feedback ($U = 47$, $r = -.32$, $p = .17$).

As the age range at T2 was broad, we used age in days as a control variable in all further analyses. Sex, which affected only the total accuracy, was also included as an additional control variable in analyses of total MR performance.

Validation of the MR task

To validate our newly developed MR task, we examined its correlation with the BiRT. BiRT scores were not normally distributed ($W(23) = 0.72$, $p < .001$) and the performance was above chance ($Mdn = 15$, $U = 300$,$p < .001$).

We calculated the partial correlation between the total accuracy in the MR task (10 trials) and the total accuracy in BiRT while controlling for age and sex. Results showed significant partial $r_s(20) = .54$, $p = .009$, $z = 0.60$. When considering only the trials without feedback and controlling for age, the correlation was also significant, partial $r_s(21) = .41$, $p = .04$, $z = 0.44$. This indicates that higher accuracy in our newly created MR task was significantly associated with higher accuracy in the BiRT.

Next, we investigated the effect of angular disparity on MR task performance, given its importance in MR measures. A repeated-measures analysis of variance (ANOVA), with accuracy at five different angles as a within-subject factor and sex as a between-subject variable, revealed a significant main effect of angle, $F(4, 88) = 2.86$, $p = .02$, $\eta_p^2 = .11$ (Fig. 2.6) and sex $F(1, 22) = 5.73$, $p = .02$, $\eta_p^2 = .20$. Post hoc t-tests showed significant differences for the angle 239.5° compared with 120° ($t(22) = 3.07$, $p = .005$, $d = 0.62$, 179.5° ($t(22) = 2.22$, $p = .03$, $d = 0.45$), and 359° ($t(22) = 3.15$, $p = .004$, $d = 0.64$). No significant differences were found among the remaining angles.

On applying Bonferroni correction, only a significant difference between 120° and 239.5° ($t(22) = 2.82$, $p = .05$, $d = .78$) and, 359° and 239.5° ($t(22) = -2.86$, $p = .05$, $d = 0.79$) was observed whereas no corrected significant difference was found between 179.5° and 239.5° ($t(22) = 2.38$, $p = .19$, $d = 0.66$). As expected, performance was notably poorer at the largest angle, 239.5°, compared with angles presented in the familiarisation video (0°-119°). The angles 120° and 359° were the easiest to perform. There seems to be a marginally significant difference in the performance at 179.5° ($p = .19$), which could be considered a moderately difficult trial. Thus, like other MR tasks, our task was also sensitive to various angular disparities.

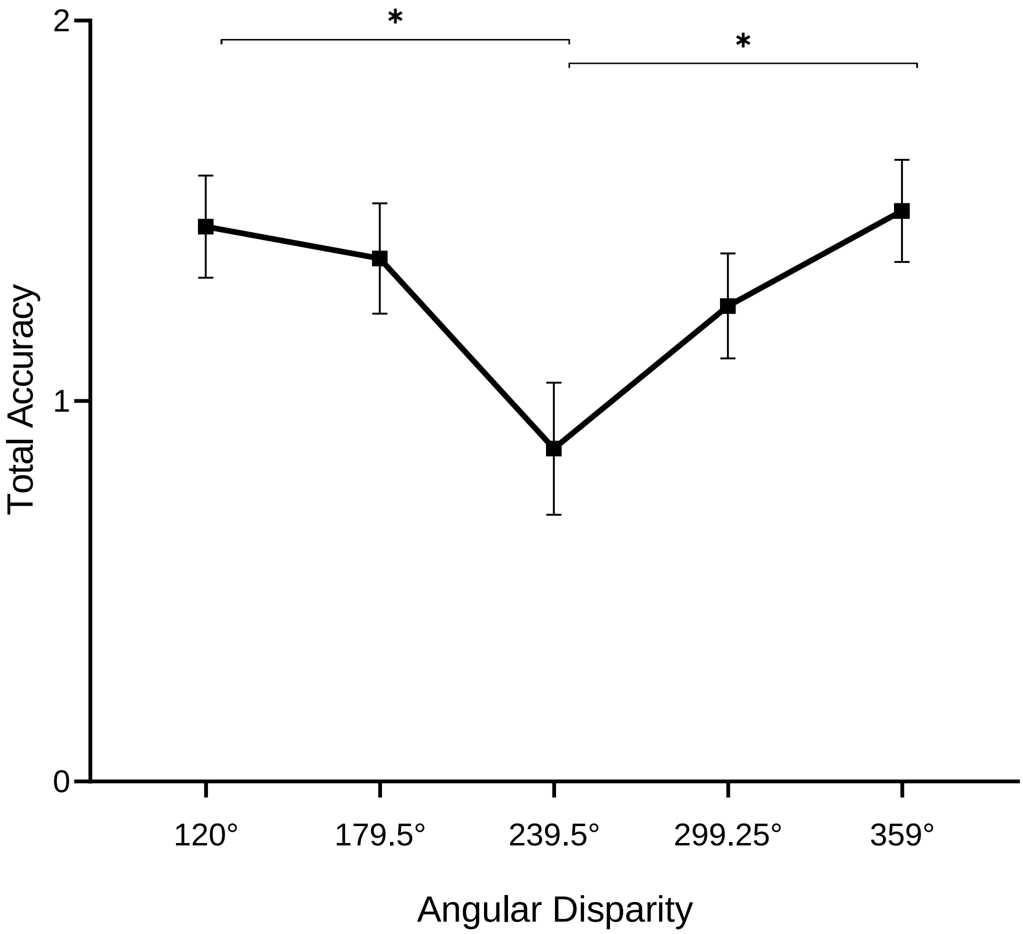

Figure 2.6: Validation of T2 MR task. Representation of the means of total accuracy (10 trials) across the different angles. As there were two trials per angle, the maximum accuracy was 2 while the minimum was 0. Error bars represent the standard error of the mean. $^{*}p < .05$.

Longitudinal Relation Analyses

A correlational analysis was used to examine the relationship between the MR performance at T1 and T2. First, we found a significant partial correlation between the difference score at T1 (infancy) and MR task score at T2 (preschoolers), controlling for age at T2 and sex, $partial\ r_s(20) = .42$, $p = .05$, $z = 0.44$ (Fig. 2.7).

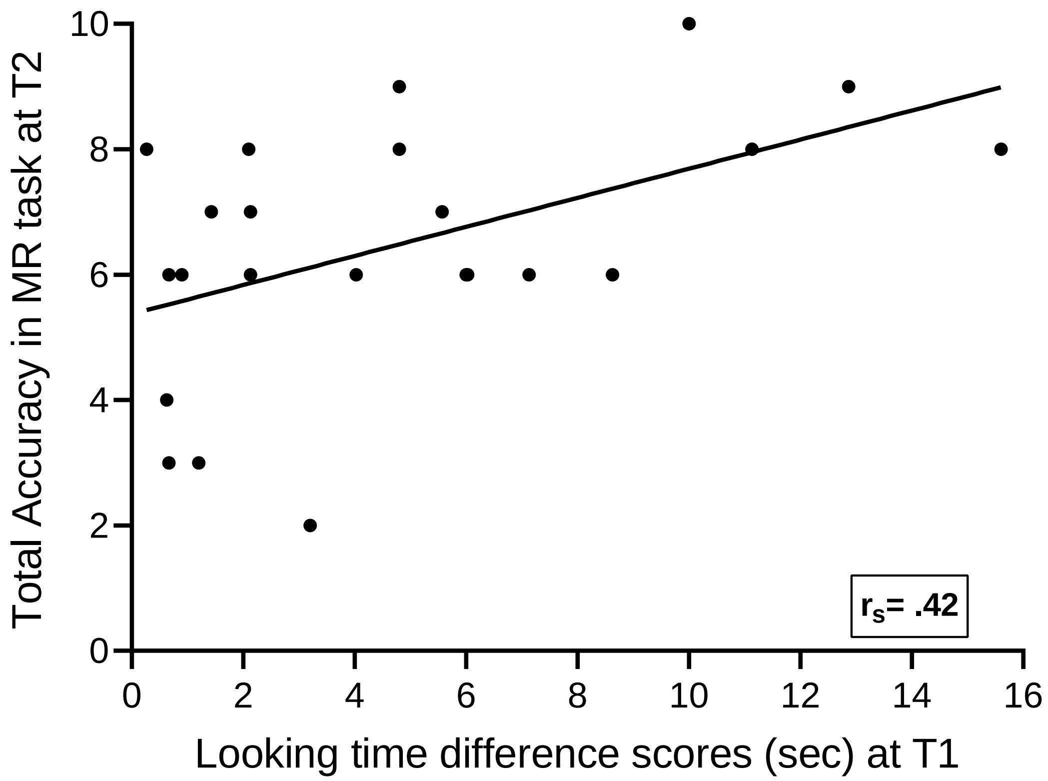

Figure 2.7: Scatterplot (with best-fitting line) indicating the relationship between MR performance in infancy using difference scores (in seconds) and preschool age using the total accuracy in the MR task.

Second, as the trials without feedback (6 to 10) were presented after the children were more familiar with how the task works, we only explored the partial correlation between these trials and the difference scores while controlling for T2 age and we found a high and significant positive correlation, *partial* $r_s(21) = .64$, $p < .001$, $z = 0.77$ (Fig.2.8). A post hoc power analysis revealed that our sample size ($n = 24$) indeed, provided high power ($1 - \beta = 0.94$) to detect the hypothesised longitudinal correlations between MR performance at T1 and T2.

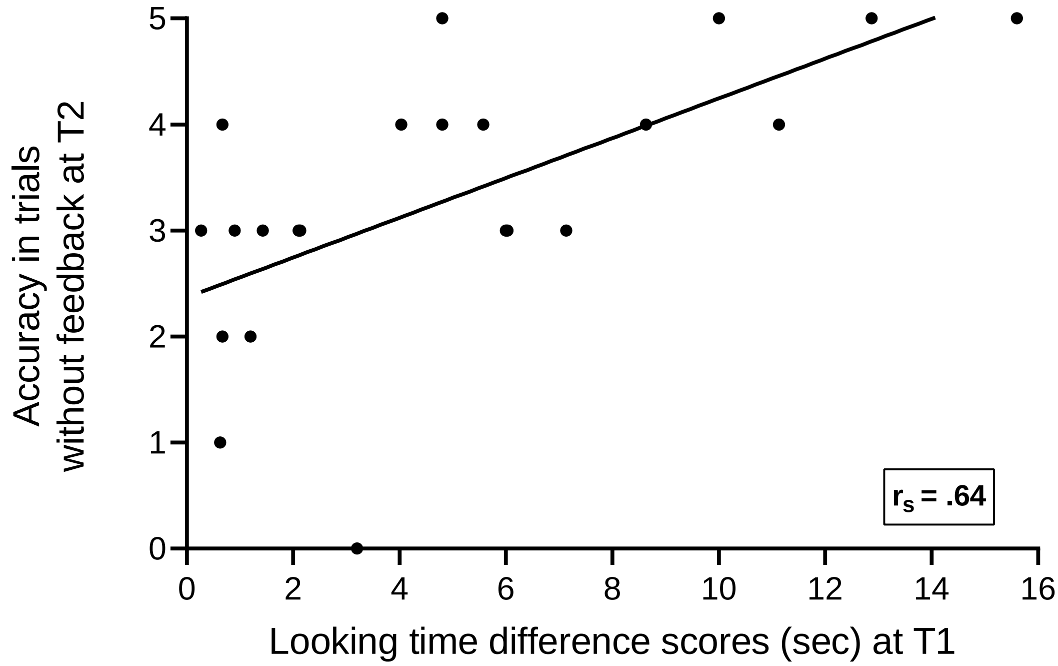

Figure 2.8: Scatterplot (with best-fitting line) showing the link between MR performance in infancy using difference scores (in seconds) and the accuracy in the trials without feedback in the MR task for preschoolers.

While controlling for intelligence using the CPM Score in addition to age at T2, the correlation between difference scores and the trials without feedback at T2, remained high and significant, partial $r_s(20) = .67$, $p < .001$, $z = 0.81$. This indicates that MR performance in infancy was strongly associated with MR performance at preschool age.

Exploratory Analysis of Motor Development and MR

To explore the link between MR accuracy and motor skills in preschoolers, a correlation analysis was conducted between total MR accuracy and the total LoMo-Score, controlling for age at T2 and sex. A significant positive partial correlation was found, partial $r_s(20) = .42$, $p = .04$, $z = 0.45$ (see Fig. 2.9). This suggests that higher MR performance was associated with greater motor development in preschoolers.

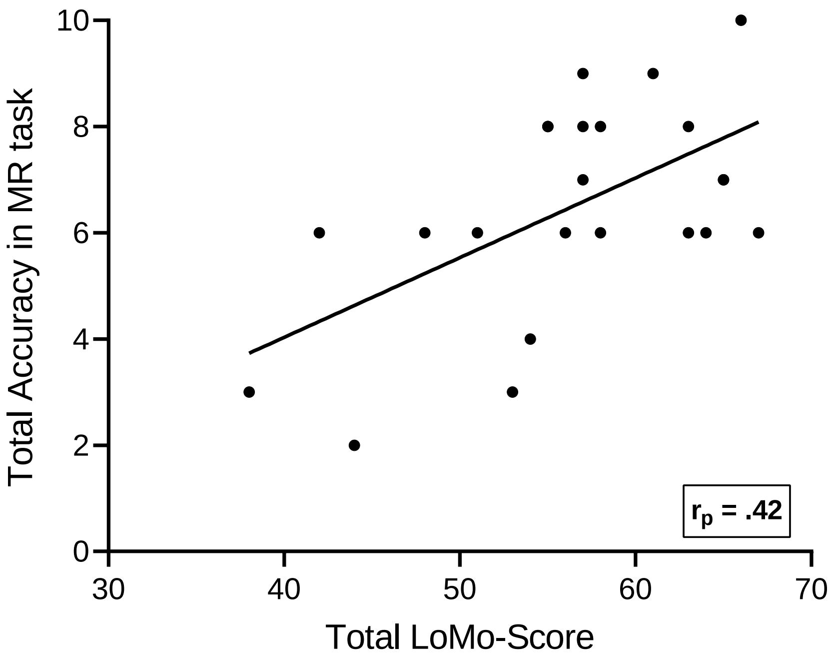

Figure 2.9: Scatterplot (with best-fitting line) representing the relationship between the total accuracy in the MR task and the total LoMo-score at preschool age.

To illuminate the longitudinal link between MR and motor skills, a point biserial correlation analysis was conducted between the infants' crawling status and preschoolers' MR performance in trials without feedback while controlling for age at T2. This analysis also revealed a positive partial correlation, $r_{pb} = .41$, $p = .05$, $z = 0.43$. Preschoolers who crawled at 9 months showed better MR performance than preschoolers who did not crawl as infants. These findings suggest that crawling status is not only associated with MR performance in infancy but also with MR performance at preschool age.

To further illustrate these findings, Table 2.1 presents the descriptive frequencies of infancy and preschool MR performance for crawlers and non-crawlers. Performance at each timepoint was classified as high or low via median split. Among crawlers ($n = 13$), 46% demonstrated high MR performance at both timepoints, whereas 64% of non-crawlers scored low at both timepoints. These descriptive patterns are consistent with the correlation findings and provide an exploratory illustration of the longitudinal relationship between crawling experience and MR performance.

Table 2.1: Longitudinal distribution of MR performance across infancy and preschool age by crawling status

Crawling Status	**Infancy MR Performance (n, %)**	**Preschool MR Performance**	
		High n (%)	**Low n (%)**
Crawlers (n = 13)	High (9, 69%)	6 (46%)	3 (23%)
	Low (4, 31%)	1 (8%)	3 (23%)
Non-crawlers (n = 11)	High (3, 27%)	3 (27%)	0 (0%)
	Low (8, 73%)	0 (0%)	8 (73%)

Note. Percentages represent the proportion within each crawling group (crawlers: n = 13; non-crawlers: n = 11). Infancy MR performance was classified as high or low using a median split of difference scores in the MR habituation paradigm. Preschool MR performance was classified as high or low using a median split of accuracy in trials without feedback in the MR video task.

A post hoc power analysis of the point biserial correlation revealed that the power was relatively low ($1 - \beta = 0.53$) to detect the hypothesised longitudinal correlations between crawling status and MR performance T2. However, this result could be a starting point to further study the potential longitudinal link between MR and motor skills.

2.6 Discussion

The primary motivation of the present longitudinal study was to determine whether infants' MR performance with 3D objects rotated in depth relates to similar 3D-MR competence in preschool age. Previous cross-sectional studies using MR tasks in preschoolers (Frick et al., 2013a; Quaiser-Pohl et al., 2010) used fairly dissimilar tasks from those used to test MR in infancy (Frick & Möhring, 2013; Linn & Petersen, 1985). Similarly, the only longitudinal study so far, conducted by Lauer and Lourenco (2016), also employed dissimilar MR tasks to test infants' (2D change detection task) and preschoolers' (mental transformation task; CMTT). To resolve this task disparity, we developed an age-adjusted MR task for preschoolers that closely resembled the infants' MR habituation paradigm by using the same stimuli and experimental logic of comparing an object with its mirror object using a screen-based format. This allowed us to assess the development of 3D-MR at 9 months and subsequently between 4.5 and 6 years of age.

The age-adjusted MR task for pre-schoolers was validated to effectively measure MR in two ways. First, performance in the MR task was significantly positively linked to the standardised BiRT test in pre-schoolers, further validating our task. Second, a main effect of angular disparity was found, consistent with the previous preschooler and adult findings (Frick et al., 2013b; Shepard & Metzler, 1971). Children found it challenging to perform well in the trials with larger angular disparities (239.5°) compared with the angles closer to those presented in the familiarisation video (120° and 359°).

The main longitudinal findings illustrate that, indeed, infant MR ability highly correlates with MR during preschool age. Most importantly, we confirmed our hypothesis by finding an even higher correlation between infants' and preschoolers' performances in comparison to Lauer and Lourenco (2016), likely due to our use of a novel age-comparable MR task. They found a correlation of r = .47 when controlling for intelligence, whereas we revealed a correlation between infants' and preschoolers' MR tasks (without feedback trials) of $r_s(20) = .67$, also when controlling for intelligence. This stronger correlation aligns with our expectation that an appropriate age-adjusted measure would better capture the continuity of MR abilities across early childhood. Thus, both studies demonstrated a significant correlation between infants' and preschoolers' visual-spatial abilities independently of intelligence, with an even higher correlation when the same visual-spatial ability, such as MR, is tested at both time points in an age-adjusted manner.

Importantly, to our knowledge, this study is the first to document this developmental link of MR using 3D stimuli rotated across depth, rather than the rotation within the picture plane (2D rotation) examined in previous longitudinal work by Lauer and Lourenco (2016). Given that 3D-MR entails reconstructing an object from unobserved parts, which is a relatively more cognitively demanding process than 2D rotation, it is particularly noteworthy that MR ability remains relatively stable over several years from infancy into preschool age. This finding broadens the understanding of spatial cognitive development and emphasises the robustness of 3D-MR as an early emerging and enduring cognitive skill.

Beyond MR, as an exploratory analysis, the role of motor development, which has been a crucial factor in facilitating MR in early years of life was also investigated. We examined whether the advantage in MR of crawling over non-crawling infants can still be observed at preschool age. Indeed, our longitudinal findings indicate a significant association between crawling status at 9 months and MR performance at preschool age, in trials without feedback. Preschoolers who had begun crawling by 9 months demonstrated superior MR performance compared to those who had not crawled at that age. This finding aligns with previous research suggesting that self-produced locomotion in infancy plays a pivotal role in the development of spatial cognitive skills, including MR (Gerhard & Schwarzer, 2018; Kelch et al., 2021; Schwarzer et al., 2022). These results serve as preliminary evidence and a first hint that self-generated locomotion in infancy may influence the visual coding of the world in a way that leads to better MR proficiency even in preschool age. This supports the theoretical view that the onset of locomotion is a critical developmental stepping stone, fostering cognitive functions such as spatial reasoning. While these motor-related findings are promising, interpretation requires caution due to the exploratory nature of the analysis and the relatively small sample sizes of crawling versus non-crawling groups, which limit statistical power and generalizability. Future, larger-scale longitudinal studies are necessary to robustly confirm and further elucidate the mechanistic pathways linking early locomotion and later MR.

Furthermore, we investigated whether preschoolers' current motor skills were related to their MR ability. Confirming the findings of Jansen and Heil (2010), our results revealed a positive correlation between the LoMo-Score and the total accuracy of the MR task at T2. This is a notable finding due to the fact that most of the studies in infancy have used 3D stimuli rotated across depth to evidence the association of MR and motor abilities; however, most of the studies in preschool age use 2D stimuli. Hence, this association suggests that the link between 3D-MR and overall motor skills persists even at an older age.

One of the limitations of the present study design was the sample size. However, considering that there were only 43 infants in the main study, we had a turnout of 24 preschoolers, which is relatively good considering the 5-year gap between the two test points. Another drawback was the limited opportunity to include additional test points, and instead, reliance on only two discrete time points for assessment. Including an additional measurement at 2 and 3 years of age would have allowed for a more nuanced conceptualisation of the developmental trajectory and a closer look during the critical transition from infancy to early childhood (Pedrett et al., 2020). Finally, further research is needed to account for the understanding of the observed sex difference in the total MR performance at T2, wherein girls performed better than boys (Enge et al., 2023).

2.7 Conclusion

This study is possibly the first of its kind to examine the longitudinal development of 3D-MR performance of children from infancy to preschool age. The study extends the previous findings on MR development by providing compelling evidence that 3D-MR abilities in infancy are significantly related to 3D-MR performance at preschool age when using an age-adjusted task, demonstrating the stability of this spatial skill across early childhood. The findings lay the foundation for future longitudinal research that systematically investigates how different motor domains interact with MR across childhood. Such work may eventually clarify whether certain motor experiences uniquely support spatial cognitive capacities, such as MR and whether motor development interventions could potentially enhance cognitive outcomes. This can have broader implications in both individual developmental and educational settings, where creating strategies for fostering the visuospatial domain and integrating motor training can potentially lead to improved spatial reasoning in early childhood, further steer stronger performance in STEM subjects, and establish finely tuned connections between action and cognition.

Chapter 3

Mental Rotation of 3D Objects in Preschoolers: Contributions of Fine and Gross Motor Skills (Study 2)

Note: A version of this chapter has been submitted for publication in *European Journal of Developmental Psychology* and is currently under review.

3.1 Background

Building on the findings of Study 1, this study extends the investigation of 3D-MR involving tangible objects in preschoolers. While screen-based paradigms allow for controlled measurement of 3D-MR processes, many everyday spatial tasks require children to interact with and orient physical objects in the environment. From an early age, children are captivated by fitting items in holes, stacking books in piles and placing lids on pans, reflecting an understanding of spatial relationships (Örnkloo & von Hofsten, 2007). MR plays a crucial role in these goal-directed tasks that require both perception and action. For instance, placing a cup in the dishwasher involves (i) mentally turning it (i.e. upside down) and (ii) then manually placing it. Despite this, MR development in preschool-aged children when using 3D tangible objects remains understudied. This is particularly notable considering that in Study 1, we found that preschoolers performed above chance in our screen-based MR task.

As reviewed in Section 1.3, preschoolers' tasks have mostly used 2D paradigms. For instance, early work by Marmor (1975), using 2D same-different judgements, demonstrated that 5-year-olds exhibit adult-like MR patterns (Shepard & Metzler, 1971), with a linear increase in RT with angular disparity. Frick et al. (2013b) devised a less cognitively demanding task using pairs of asymmetrical flat ghost figures alongside a cut-out board for children below five. Children had to select and orient the figure to fit the cut-out correctly. Results showed a developmental trend, wherein 3-year-olds performed at chance level, while 5-year-olds performed above chance, with a linear decrease in accuracy percentage as angular disparity increased. 2D-MR in preschoolers is further supported by eye-tracking (Rodriguez et al., 2025) and touchscreen paradigms (Frick et al., 2013a). However, MR studies using 3D objects remain surprisingly underexplored in preschoolers. It is plausible that 3D-MR is cognitively more demanding than 2D-MR because it involves mental reconstruction of non-visible parts of the object, whereas 2D-MR requires only rotation along a single axis (Jolicœur et al., 1985; Shepard & Metzler, 1988). One notable attempt by Hawes et al. (2015a) utilised 3D tangible objects to develop an age-appropriate MR task for 4- to 8-year-olds. They presented four objects: a target object, a rotated object, a mirror object and a structurally dissimilar distractor. Children matched the rotated object with the target objects' orientation and were classified according to their performance. While 8-year-olds had low error rates and were successful rotators, 4-year-olds were mostly classified as mirror-confused. Although their 3D-MR task correlated with the 2D-MR Task (Levine et al., 1999), they did not assess the effect of angular disparity, a hallmark of MR, highlighting the imperative need for comprehensive research on 3D-MR in preschoolers.

Although research on MR in infancy, which predominantly employed 3D stimuli, has demonstrated close links with motor development (See Section 1.2.3 for overview), including crawling and manual object exploration Schwarzer et al. (2013b) and Soska et al. (2010), research with preschool children has largely focused on 2D-MR tasks when examining associations with motor skills. For instance, Frick et al. (2009) demonstrated that manual rotation had an influence on 2D-MR in children aged 5 to 8 years, and Jansen and Heil (2010) reported an association between 2D-MR abilities and motor coordination and body agility. Despite the compelling evidence linking motor experience and MR in infancy, the relationship between motor skills and 3D-MR in preschool children remains unexplored. Moreover, the development of both fine and gross motor skills across childhood necessitates a nuanced understanding of their relation with 3D-MR. While an amalgamation of both fine and gross motor skills may influence MR in infancy, the onset of writing, numerical and other educational activities, involving hand-eye coordination (Yuniarwati & Lin, 2025), may suggest that fine-motor skills become more related to MR as children mature. To date, to the best of our knowledge, no study has directly investigated the association between 3D-MR and motor abilities in preschool children. This represents an important gap, particularly given evidence suggesting continuity between early motor experience and later spatial cognition in Study 1. Hence, this study investigates whether the association between 3D-MR and motor skills found in infancy persists in preschoolers.

3.2 Objectives

Study 2 aims to investigate the developmental differences in 3D-MR between younger (4.6– to 5.5-year-olds) and older (5.6- to 6.5-year-olds) preschoolers, as well as the link between fine and gross motor skills. To this end, a novel 3D-MR Block Task was developed to investigate both perception and action phases of MR using the Shepard Metzler objects used in Study 1, but were 3D printed. Similar to Study 1, the LoMo assessment (Jaščenoka & Petermann, 2018) was administered to measure both fine and gross motor skills, and the BiRT test (Quaiser-Pohl, 2003) was used to validate the novel 3D-MR Block Task.

3.3 Methods

3.3.1 Sample

The study complied with the German Psychological Society (DGPs) Ethics Guidelines and was approved by the Ethics Office at the University of Giessen. Written parental consent was obtained after confirming children's willingness to participate. Seventy preschoolers (32 males) from middle-class families were recruited via local birth records; two were excluded (one: fussiness, one: incomplete tasks). The final sample included 39 children aged 4 years 6 months to 5 years 5 months (M = 4 years 9 months; SD = 3 months; 15 males) and 29 children aged 5 years 6 months to 6 years 5 months (M = 5 years 9 months; SD = 4 months; 16 males). Participants were predominantly Caucasian, residing in Giessen and nearby suburban areas. All spoke German, and all tasks were administered in German. Children received a sticker after each task and a certificate, plus a toy.

3.3.2 MR Tasks

Bilder Rotations Test

Similar to Study 1, children first completed the German Picture Rotation Test (BiRT; (Quaiser-Pohl, 2003). A detailed description of the test is provided in Section 2.3.3.

MR Block Task

Stimuli

The stimuli were 3D tangible Shepard-Metzler objects, an L- and an R-object, mirrored versions of each other, created in Blender 2.79 (Blender Online Community, 2017) and 3D printed (Kelch et al., 2021). Each measured 10 × 7.5 × 5 cm. The L-object's faces were coloured red (back), dark purple (front), orange (top), yellow (bottom), pink (left), and ochre (right); the R-object had the same colours but mirrored (Fig. 3.1). Corresponding white round boxes (16 cm diameter, 6 cm height) with L-shaped (L-Box) or inverted L-shaped (R-Box) 3D cut-outs fit the objects. Each box had a round cardboard lid placed when the correct object was fitted (Fig. 3.2).

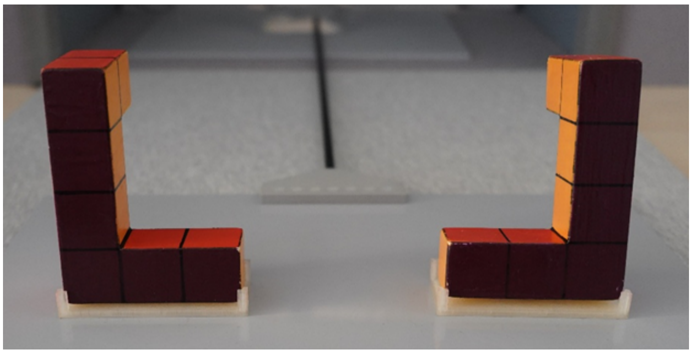

Figure 3.1: Stimuli objects of the MR Block task. Front view of L-object (left) and R-object (right).

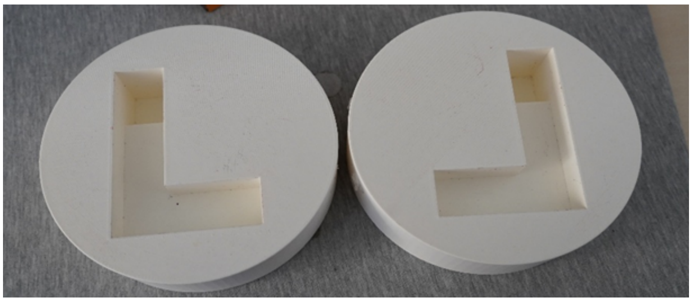

Figure 3.2: Stimuli boxes of the MR Block task. L-Box (L-shaped cut-out, left) and R-Box (inverted L-shaped cut-out, right). Each object fits its corresponding box.

Apparatus

The experiment used a theatre setup (80 × 60 cm) with a 45 × 37.5 cm cut-out covered by a cardboard occluder, placed on a 100 × 60 × 74 cm table. A grey wall behind prevented the child from looking behind the theatre. One camera filmed the child's hand movements and face from the rear wall once the occluder was lifted, and another recorded from the child's left side. Objects were placed on a grey metal plate (33 × 24 cm) with a rod allowing it to be pushed forward for the child to reach (Fig. 3.3). Two trained experimenters conducted the task: one placed objects behind the theatre, the other instructed and observed the child from the left side.

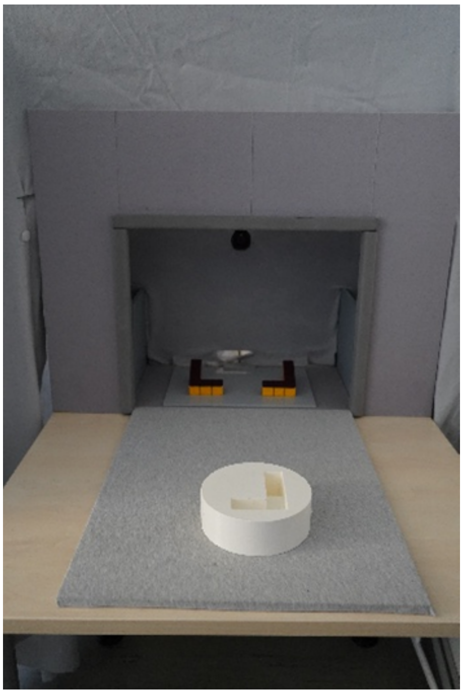

Figure 3.3: Theatre setup for MR Block task

Procedure

Children sat in front of the theatre, positioned to see and reach objects clearly. The cover story involved helping a clown, Seppi, collect magic stones to build a circus arena. After two practice trials with simple objects, ten test trials using L- and R-objects were conducted.

Practice Trials: Children completed two practice trials using simple non-mirrored objects ('T' and '+') with matching boxes. The instructor placed a box in front of the child, and the experimenter positioned both objects on a plate behind the theatre. Children were asked to examine the box cut-out and indicate which object would fit (perception phase). The plate was then moved forward, and children inserted the object into the box (action phase). Correct fits were shown by placing a lid on the box; incorrect fits were demonstrated when the lid did not close.

Test trials: Either the L- or R-Box was placed before the child. After repeating the instructions as above, children were told the objects would look different (see Fig. 3.4). The experimenter positioned the L- and R-objects on the metal plate, and the task was conducted as above. The task consisted of 10 test trials lasting 10-15 minutes, and accuracy in pointing and fitting was measured.

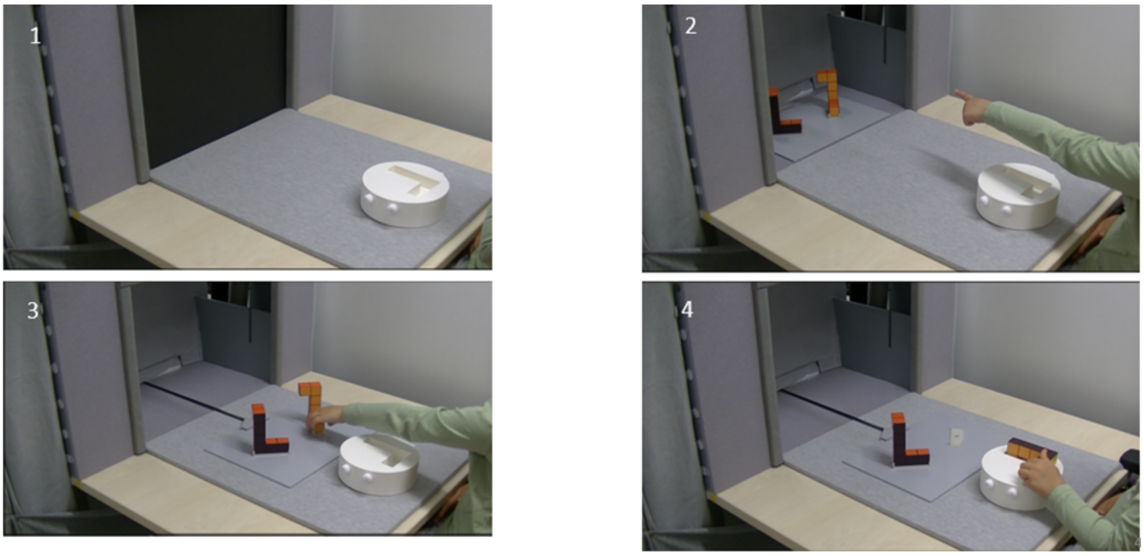

Figure 3.4: Representation of a test trial. Images 1-2 show the perception phase (pointing after occluder is lifted); Images 3-4 show the action phase (grasping and fitting the object).

Design

The test trials varied in angle (0°, 45°, 90°, 135°, 180°) and axis of rotation (X or Y), each presented twice (once per axis) for a total of 10 trials (Fig 3.5). Each child saw only one box (L- or R-Box) in a fixed orientation. Box type and correct object position (left/right) were counterbalanced by age and sex. Objects on the left rotated clockwise, those on the right rotated anticlockwise. The order of angles was consistent for all children, starting with 0° rotation on the X-axis. See Appendix 6 for the randomisation plan and position information.

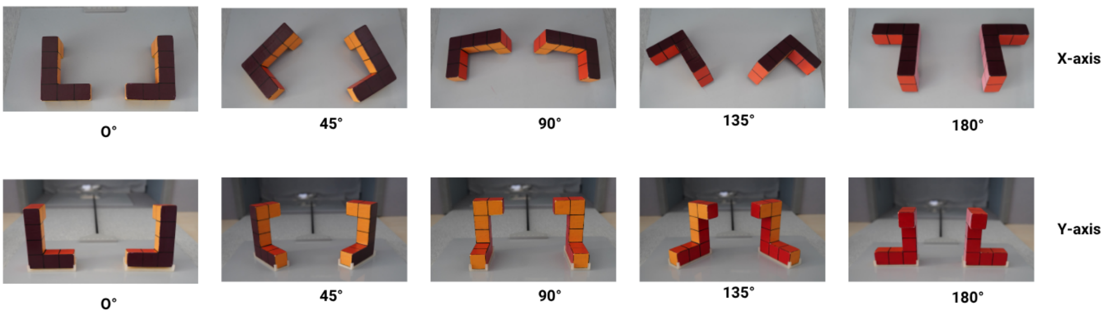

Figure 3.5: Stimuli orientation in the MR Block task. Orientations of the L-object (left side) and R-object (right side) with varying angular disparity and two axes of rotation (shown from the child's perspective).

Motor Test

Similar to Study 1, we administered version B of the Leistungsinventar zur objektiven Überprüfung der Motorik (Jaščenoka & Petermann, 2018), a standardised German test for fine and gross motor skills in children aged 4.6 to 6.11 years. A detailed description of the test is provided in Section 2.3.3.

3.4 Data Coding and Scoring

3.4.1 Behavioural Coding of the MR Block Task

Responses were coded in two phases: perception and action. In the perception phase, children pointed to the object they believed to fit the box after the occluder was lifted. In the action phase, they tried to fit the chosen object once it was pushed forward. Accuracy was scored separately for each phase (1 point: correct, 0 points: incorrect), with a maximum of 10 points per phase. Trials were incorrect in action if the wrong object was fitted, but touching the wrong object without fitting it first was scored as correct. Separate scores were also calculated for each axis (X and Y), with a maximum of five points per axis.

3.4.2 Evaluation of LoMo Assessment

Similar to Study 1, items were scored according to the manual to calculate a Total LoMo Score (maximum = 74), which comprises both fine and gross motor tasks. Additionally, separate scores were also computed for each domain: fine motor (32 points; e.g., drawing, folding, threading, tapping) and gross motor (42 points; including coordination: balancing, jumping jacks; strength/endurance: running, stopping; and object control: throwing, catching).

3.5 Results

3.5.1 Preliminary Analysis and Validation of the MR Block Task

Both older children and younger children performed above chance in both perception and action phases (see Fig. 3.6)

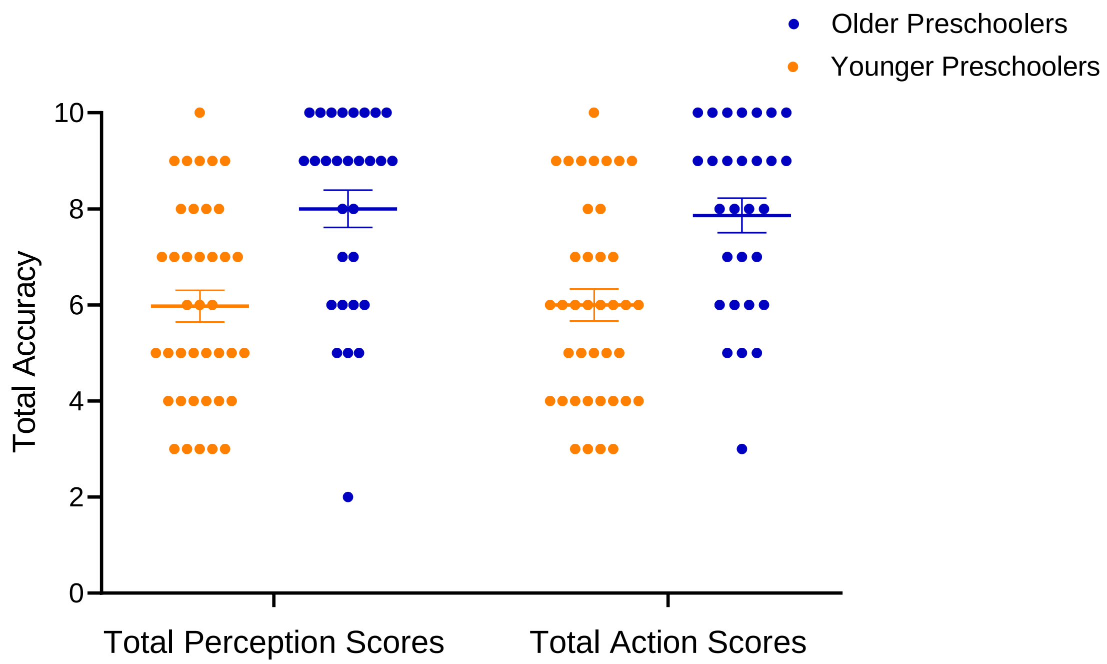

Figure 3.6: Distribution of perception and action scores in younger and older children. Both scores range from 0 (minimum) to 10 (maximum). Horizontal line represents the mean and the error bars represent standard error of the mean.

One-sample t-test indicated that older children performed significantly above chance on both perception (M = 8.00, SD = 2.08), $t(28) = 7.74$, $p < .001$ and action phase (M = 7.86, SD = 1.94), $t(28) = 7.94$, $p < .001$. Younger children performed slightly above chance in perception (M = 5.97, SD = 2.05), $t(38) = 2.95$, $p = .005$ and action phase (M = 6.0, SD = 2.07), $t(38) = 3.00$, $p = .005$.

A mixed-design ANOVA examined accuracy with axis of rotation (X vs. Y) and task phase (perception vs. action) as within-subject factors, and age group (younger vs. older), box condition, and sex as between-subject factors. There was no main effect of axis, $F(1, 60) = 0.02$, $p = .88$, $\eta_p^2 = .0003$, nor of phase, $F(1, 60) = 0.18$, $p = .67$, $\eta_p^2 = .003$, indicating that performance was similar across axes (X: M = 6.80, SE = 0.31; Y: M = 6.82, SE = 0.31) and phases (perception: M = 6.83, SE = 0.27; action: M = 6.79, SE = 0.26). Sex also had no significant effect, $F(1, 60) = 0.07$, $p = .78$, $\eta_p^2 = .001$ (males: M = 13.67, SE = 0.82; females: M = 13.59, SE = 0.71). As expected, age had a significant effect, $F(1, 60) = 16.44$, $p < .001$, $\eta_p^2 = .21$, with older children (M = 15.86, SE = 0.74) outperforming younger children (M = 11.97, SE = 0.64). There was also a significant axis × phase interaction, $F(1, 60) = 4.99$, $p = .02$, $\eta_p^2 = .07$. However, Bonferroni-corrected post hoc comparisons revealed no significant differences between axes within phases or between phases within axes (all ps > .57).

A significant main effect of box condition was observed, $F(1, 60) = 5.63$, $p = .02$, $\eta_p^2 = .08$. Bonferroni-corrected post hoc comparisons indicated a significant difference between the two box conditions ($p = .02$), with children performing better in the R-Box condition (M = 14.83, SE = 0.68) than in the L-Box condition (M = 12.62, SE = 0.77).

Hence, the data were collapsed across these factors (maximum aggregated MR score: 4 per angle, 20 overall). Box condition was retained as a between-subjects control. Sex showed no effect and was excluded from further analyses.

To validate the novel MR Block task, partial correlations with BiRT scores were computed, controlling for box condition. Results showed significant positive correlations for younger children, partial $r_p(36) = .32$, $p = .05$, and for older children, partial $r_p(26) = .44$, $p = .01$, indicating that MR Block performance is related to standardized MR measures, supporting its validity for assessing 3D-MR in preschool-aged children.

3.5.2 Main Statistical Analysis

MR Block Task

A repeated-measures ANOVA was conducted with angular disparity (0°, 45°, 90°, 135°, and 180°) as the within-subject factor, and age group (younger vs. older) and box condition (L-Box vs. R-Box) as between-subject factors. The dependent variable was the aggregated MR score. The analysis revealed a significant main effect of angular disparity, $F(4, 256) = 4.28$, $p = .002$, $\eta_p^2 = .06$, indicating that performance decreased with increasing rotation angle (see Fig. 3.7). Bonferroni-corrected post hoc comparisons based on estimated marginal means revealed that 0° trials ($M = 3.001$, $SE = 0.15$) produced higher accuracy than 180° trials ($M = 2.26$, $SE = 0.15$, $p = .003$); 45° trials ($M = 2.85$, $SE = 0.15$) were higher in accuracy than 180° trials ($p = .03$); and 90° trials ($M = 2.87$, $SE = 0.15$) were easier to perform than 180° trials ($p = .02$).

A significant main effect of age group, $F(1, 64) = 16.59$, $p < .001$, $\eta_p^2 = .20$, indicated that older children ($M = 15.86$, $SE = 0.74$) outperformed younger children ($M = 11.97$, $SE = 0.64$). A significant main effect of box condition, $F(1, 64) = 4.95$, $p = .03$, $\eta_p^2 = .072$, indicated that children presented with the R-Box ($M = 14.83$, $SE = 0.68$) outperformed those with the L-Box ($M = 12.62$, $SE = 0.77$). No other interaction effects were significant.

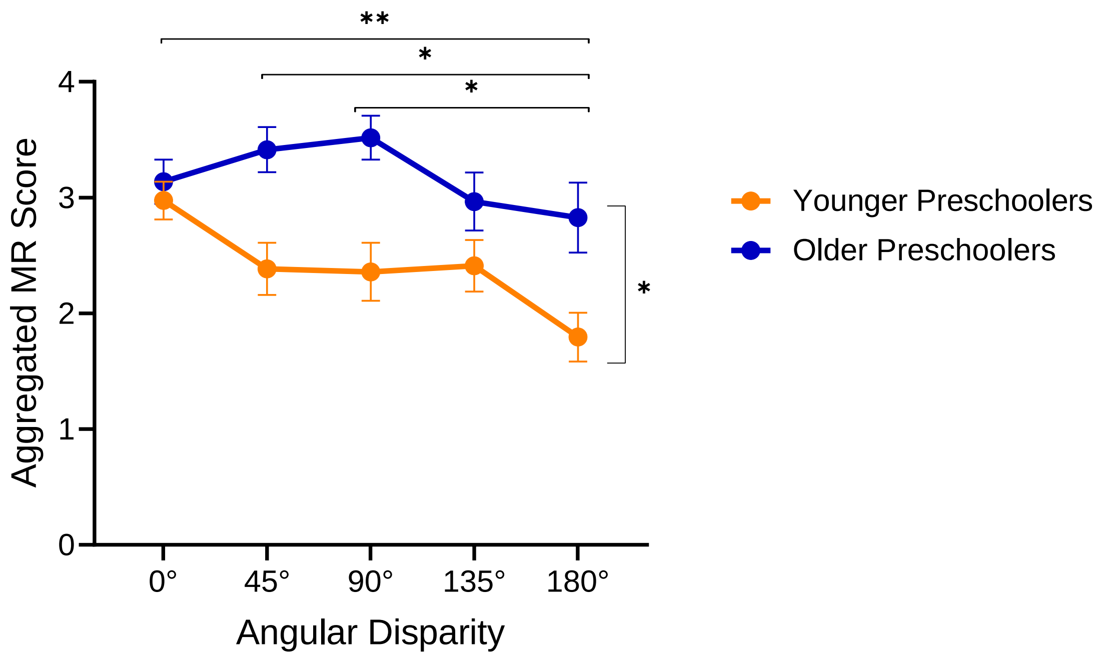

Figure 3.7: Mean aggregated MR score in the 3D-MR Block task across five angles for younger and older preschoolers. Horizontal brackets indicate significant differences between 0°, 45°, 90°, angular disparity conditions and 180°. Vertical brackets indicate significant main effect of age. Error bars represent the standard error of the mean. $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$.

Post hoc power analysis for the within–between interaction ($f = 0.2$, 2 groups, 5 measurements, $\alpha = .05$) using G*Power (Faul et al., 2007) yielded a power of 0.99 for the main effect of angular disparity, indicating an adequate sample size.

Motor Skills and MR

An independent samples t-test confirmed that older preschoolers (M = 56.75, SD = 7.28) had significantly outperformed the younger preschoolers (M = 49.56, SD = 8.86) in motor performance, $t(66) = -3.56$, $p < .001$.

Fig.3.8 illustrates the developmental relationships between MR and motor performance outcomes. Aggregated MR, gross motor, and fine motor scores were dichotomised using median splits to form high- and low-performance groups. As shown, children with higher MR ability predominantly exhibited high gross motor performance across both age groups, whereas lower MR ability was more strongly associated with lower gross motor outcomes. Among older participants, high MR ability was also linked to a concentrated flow toward high fine motor performance, suggesting an increasing alignment between visuospatial cognition and fine motor control with age. In contrast, younger participants displayed a more diffused pattern, with both high and low MR scorers connecting to a range of fine motor outcomes. Collectively, these patterns indicate a developmental shift, whereby differentiation in fine motor performance as a function of MR ability becomes more pronounced in later childhood.

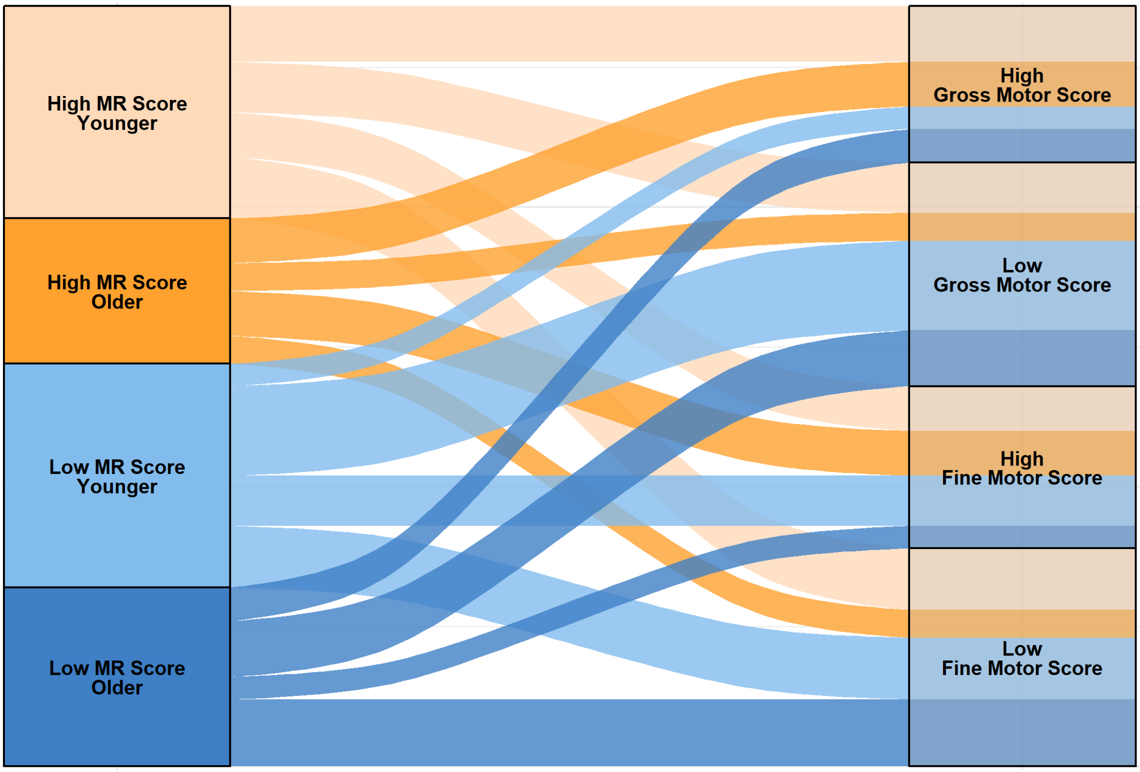

Figure 3.8: Sankey diagram of 3D-MR and motor subgroups in younger and older preschoolers. Flow thickness represents the number of children in each group. The left side shows high and low 3D-MR subgroups, and the right side shows the corresponding high and low gross and fine motor subgroups.

To determine how motor skills affect 3D-MR, a hierarchical linear regression was conducted with aggregated MR scores as the dependent variable and age group, box condition, and gross and fine motor skills as predictors. In Model 1, age group and box condition significantly predicted MR performance, $R^2 = .25$, $F(2, 65) = 11.26$, $p < .001$. Older children outperformed younger ones ($b = 3.91$, $p < .001$), and the L-box condition was more difficult than the R-box ($b = 2.26$, $p = .01$).

In Model 2, gross and fine motor skills were added, yielding a significant improvement in model fit, $\Delta R^2 = .11$, $\Delta F(2, 63) = 5.16$, $p = .008$. The model accounted for 36% of the variance, $R^2 = .36$, $F(4, 63) = 8.78$, $p < .001$. Gross motor skills significantly predicted MR performance ($b = .24$, $p = .01$), whereas fine motor skills were not significant ($p =$ .63).

In Model 3, the interaction terms (fine motor × age and gross motor × age) were entered. The final model was significant, $R^2 = .39$, $F(6, 61) = 6.49$, $p < .001$, but the increase in explained variance was not significant, $\Delta R^2 = .03$, $\Delta F(2, 61) = 1.85$, $p = .16$. The fine motor × age interaction emerged as significant ($b = .51$, $p = .05$), suggesting that fine motor skills predicted MR performance only among older children. However, the gross motor × age interaction was not significant. These findings suggest a developmental shift in the relation between MR and fine motor skills in older children.

A post hoc power analysis of the regression ($\alpha = .05$) showed that Model 2 had moderate power ($f^2 = 0.14,\ 1-\beta = 0.77$), whereas Model 3 had low power ($f^2 = 0.06,\ 1-\beta = 0.40$), suggesting that the results should be interpreted cautiously.

3.6 Discussion

This study elucidated 3D-MR development using a block task and its relation to motor skills in preschoolers. Our findings demonstrated a significant increase in 3D-MR between ages 4.6 to 6.5, indicating the refinement of MR throughout early childhood. Additionally, gross motor skills predicted 3D-MR ability across ages, whereas fine motor skills seemed to predict 3D-MR only in older children, suggesting evolving motor-cognitive links throughout preschool years.

We confirmed the developmental trend of 3D-MR in preschoolers and extended insights across various aspects. Consistent with the findings of Study 1, the first insight involved validating our novel 3D-MR Block task through a significant correlation with a standardised 2D-MR test (BiRT), thereby replicating the previous 2D/3D-MR association (Hawes et al., 2015a). Additionally, we found our 3D-MR block task's sensitivity to angular disparity, mirroring the pattern observed in our screen-based MR task in Study 1. Consistent with classic findings of Shepard and Metzler (1971), 180° rotations posed the greatest challenge. While younger children's accuracy decreased with increasing disparity, older children displayed higher accuracy at 90° compared to 0° and 45° (Fig.3.7. Our MR Task was also robust to the axis of rotation which could be explained by the presence of a protruding part on the objects, potentially serving as a "mental anchor" (Hawes et al., 2015a), offering a consistent reference point that reduced axis-related difficulty. Additionally, children demonstrated greater difficulty in identifying and fitting the correct object in the L-Box than in the R-Box condition. This could be because some children attempted to solve the task by searching for the letter L in the L-Box condition. However, when the R-object was rotated by larger angles, it resembled an 'L'. In such cases, if the children could not inhibit searching for the L, they might incorrectly select the R-object, even though it was an L-Box. By contrast, in the R-box condition, a similar strategy could not be used because recognising and searching for a letter was less obvious than in the L-Box condition. The three-way age-sex-box-condition interaction could be due to the L-Box being challenging for younger children, and apparent sex differences may reflect the interaction of this with age rather than indicating genuine sex-based differences. Although reported in some infant studies (Enge et al., 2023), there are no consistent sex differences in children below 10 (Frick et al., 2013b; Hawes et al., 2015a; Jansen et al., 2013).

Furthermore, we present the novel evidence suggesting parallels between the perception-action phases within a 3D-MR task. Consistent with findings of tasks requiring manual-object rotation in the shortest path in 3- to 6-year-olds (Krüger et al., 2014a), our results demonstrated an alignment between perceptual processing and grasping decisions, suggesting that both develop in tandem during early childhood. Moreover, the perceptual phase, which entails encoding the target and subsequently identifying it, followed by the action phase, involving manual manipulation and object fitting, aligns closely with the MR framework proposed by Just and Carpenter (1985) and further elaborated by Heil and Rolke (2002). This correspondence suggests that the sequential cognitive processes underlying MR are also potentially captured within the structure of this task.

Another key finding is the association of 3D-MR with motor skills in preschoolers, suggesting that the 3D-MR and motor skills association found in infancy persists during preschool age. This finding aligns closely with the results of Study 1, in which preschoolers' motor abilities were also significantly related to performance on a screen-based MR task. Furthermore, it aligns with neuroimaging evidence in previous literature implicating shared neural representations of movement and MR (Zacks, 2008). As anticipated, older children displayed superior motor proficiency compared to younger ones. The Sankey diagram (Fig.3.8) illustrates these developmental patterns, with stronger flows in both younger and older preschoolers, with higher 3D-MR showing better gross motor performance, but in older ones, the flow toward fine motor ability was especially prominent, reflecting a developmental shift. Regression models confirmed this differentiation, indicating that gross motor skills predicted 3D-MR across age, while fine motor ability predicted 3D-MR only in older preschoolers. These findings align with the theoretical accounts emphasising embodied foundations for 3D-MR in early preschool years, where whole-body movements scaffold fundamental spatial concepts and coordinate systems (Adolph & Franchak, 2017). In contrast, as children mature, the environmental demands within educational contexts, such as writing and puzzle-solving (Levine et al., 2012), or the prevalence of technology use, likely foster and shape the fine-motor system for manual control and coordination. This shift toward fine-motor prominence is consistent with findings in school-age populations, where manual dexterity demonstrates associations with 2D-MR (Fernández-Méndez et al., 2020) and fine, but not gross-motor skills, predict mathematical ability (Morales et al., 2011). As our 3D-MR task involved fine-motor skills, it is foreseeable that older children performed better in both the MR task and the fine-motor test. However, the interaction effect observed in the regression model was underpowered and should be interpreted cautiously, suggesting a potential developmental shift in which different motor domains may support MR development across age.

A major limitation of our study is the small sample size, which reduced the statistical power, particularly for interactions involving motor skills. Furthermore, the ceiling effect in the 3D-MR task among older children, likely due to the inherent feedback in every trial, suggesting that more challenging stimuli could better capture individual differences.

Future studies integrating eye-tracking and motion-tracking may illuminate the real-time interaction between perceptual-motor domains.

3.7 Conclusion

To conclude, 3D-MR improves significantly in preschoolers and might be differentially linked to gross and fine motor skills during this period, suggesting that different components of the motor system may support MR during early childhood. Moreover, the close coupling of perceptual and action-based processes observed here indicates that these systems develop in tandem during early development, rather than independently. Taken together, these results provide an empirical foundation for the design of targeted educational and intervention approaches aimed at supporting MR and broader spatial skills in early childhood.

Chapter 4

Mental Rotation, Visual Prediction, and Motor Skills in Infancy: An Integrative Exploration (Study 3)

4.1 Background

Study 3 extends the investigation of visuospatial abilities by examining a previously unexplored link between two core abilities: visual prediction and MR. As outlined in Section 1.1.2, spatial cognition can be described within a 2 × 2 typology (Newcombe et al., 2013) that distinguishes between intra-object and inter-object processing. Studies 1 and 2 examined infants' intra-object spatial processing in isolation and provided evidence for a link between these abilities and motor development. Despite this theoretical distinction, empirical evidence on how intra- and inter-object spatial processes are related during early development remains limited. Visual prediction and MR both involve tracking and mentally simulating 3D object transformations. As such, they may rely on shared cognitive mechanisms and may jointly supported by motor experience. Although existing findings strongly support links between motor development and visual prediction (Kubicek et al., 2017b) on the one hand, and motor development and MR (Schwarzer et al., 2013b) on the other hand, whether visual prediction and MR are themselves related during infancy remains entirely unexplored. The present study, therefore, directly addresses this gap by investigating whether infants who show stronger visual prediction abilities also demonstrate better MR performance, and whether motor skills play a supporting role in the development of both abilities.

Successful prediction of an object's future location or orientation depends on at least two core cognitive abilities: maintaining a mental representation of an object when temporarily out of view known as, object permanence, Piaget (1952) and anticipating its future trajectory (Kubicek et al., 2017a). A growing body of research indicates that motor experience shapes these prediction abilities. Gehb et al. (2023) found that 6-month-old pre-locomotor infants improved in visually anticipating the reappearance of occluded objects only after receiving passive motion experience, but not after active motion training or no training. Hence, the authors concluded that visual information gathered during even passive movement seemed sufficient for visual prediction. Similarly, Kubicek et al. (2017b) reported that crawling 9-month-old infants predicted occluded object trajectories more successfully than non-crawlers when viewing a rotating 3D object array. Using the same paradigm, Kubicek et al. (2017a) further showed that infants who engaged in more varied manual object exploration demonstrated higher prediction rates. Together, these findings suggest that both locomotor and manual motor experience contribute to the development of visual prediction in infancy, complementing the motor-MR links established in Studies 1 and 2.

The only study to have examined the relation between visual prediction of rotational motion and MR was conducted by Pedrett et al. (2020). Using an eye-tracking paradigm, toddlers (aged between 22 and 38 months) viewed animations of an object resembling the letter “p” rotating clockwise around its foot. The object disappeared behind a pie-shaped occluder and reappeared either in its correct orientation or as a mirror-reversed version (i.e., a “q”). Analyses of eye movements during the visible rotation revealed developmental changes in how toddlers encoded rotational motion. Younger toddlers primarily tracked the outer edge of the rotating object, whereas older toddlers increasingly alternated their gaze between the outer edge and the pivot point. This shift suggests a more sophisticated encoding strategy: tracking only the outer edge provides information about circular motion, while incorporating the pivot point allows encoding of changes in object orientation, a defining feature of rotation. When the object disappeared behind the occluder, older toddlers also showed earlier and more predictive gaze shifts to the reappearance side and looked back less often toward the disappearance side. Together, these findings indicate that with age, toddlers formed increasingly stable mental representations of rotational motion. However, it remains unclear whether these representations involved mentally simulating changes in object orientation or merely tracking the object’s circular trajectory. To address this question, they compared toddlers’ looking times following correct versus mirror-reversed reappearances. If toddlers had formed detailed MR, longer looking times were expected for mirror-reversed outcomes. Contrary to this prediction, looking times did not differ between conditions. Unlike findings from younger infant samples (Frick & Möhring, 2013; Möhring & Frick, 2013), this study did not provide clear evidence for MR at a level of precision sufficient to distinguish mirror images in 2- to 3-year-olds. Nevertheless, because looking time is an indirect measure, it cannot be ruled out that toddlers detected the mismatch without expressing it behaviourally. The study additionally included an object-fitting task in which toddlers were asked to insert elongated wooden blocks into apertures in a box. With increasing age, toddlers more frequently pre-adjusted the orientation of the blocks and showed higher insertion success, replicating previous findings (Örnkloo & von Hofsten, 2007). Correlational analyses revealed meaningful links across tasks. Toddlers who made more gaze shifts between the outer edge and pivot point during visible rotation also showed earlier anticipatory looks to the reappearance side, suggesting that encoding visible rotation is related to forming predictive representations of motion. Although this pattern could reflect individual differences in general visual exploration, anticipatory gaze behaviour also correlated with pre-adjustments in the object-fitting task, even after controlling for age and overall visual attention. Toddlers who predicted the object's reappearance earlier were also more likely to orient the blocks appropriately before insertion. This convergence across perceptual and motor tasks suggests a shared underlying process, namely a rudimentary ability to imagine or anticipate rotational transformations.

Taken together, the findings reviewed above point to an important gap in the literature: although visual prediction and MR have each been studied in 9-month-olds, the relation between these two abilities has not yet been directly examined. Because both involve tracking and mentally simulating 3D object transformations, it is plausible that they rely on shared cognitive mechanisms.

4.2 Objectives

This study aimed to investigate the relation between 3D-MR and visual prediction in infants aged 9 to 12 months. The well-established 3D-MR habituation paradigm from Study 1 was employed alongside a novel screen-based prediction task, with gaze behaviour captured using eye-tracking. A further objective was to examine whether gross motor skills are associated with performance in both tasks. Given the early stage of data collection, the present chapter reports the findings of the pilot study.

4.3 Methods

4.3.1 Sample

This study was conducted in accordance with the ethical guidelines of the German Psychological Society (DGPs). The Office of Research Ethics at Justus Liebig University Giessen approved both the experimental procedures and the informed consent protocol. Written informed consent was obtained from the parents of all participating children before the study. Infants were recruited through local birth records from the city of Giessen. A total of 23 infants (between 270 and 380 days of age) participated in the study ($Mdn = 319 days$, $SD = 26.8$ days; 10 males). This study served as a pilot for the main experiment, which is currently ongoing. The results reported here refer solely to this pilot phase.

4.3.2 MR Task

As mentioned in Study 1, we used the same infant habituation task to measure MR. See details of the task, including apparatus, stimuli, and procedure in Section 2.3.2.

4.3.3 Visual Prediction Task

To measure the prediction ability in two locations, we created a screen-based task which was adapted from Kubicek et al. (2017b).

Stimuli

We created the task in Blender (Blender Online Community, 2024). The primary occluding object consisted of a rectangular surface divided into two halves: blue on the top and red on the bottom. This occluder visually concealed a block positioned directly behind it, painted identically to the occluding surface (blue top, red bottom). On either side of the block, grooves were simulated to indicate potential placements for two target objects. The two naturalistic target objects, a frog and a cow, emerged from different positions (top and bottom or left and right) on the array depending on the experimental phase. As in the original setup, the digital version ensured that targets were fully hidden from view when the array was observed from the front, maintaining the occlusion effect.

The task consisted of a familiarisation and a test phase, each comprising six trials. During the familiarisation phase, the array rotates back and forth around its vertical axis. The frog was presented consistently on the left side when the array rotated to the right; conversely the cow appeared on the right side when the array rotated to the left. During the test phase, the array was rotated by 90°, causing the red and blue panels to appear vertically aligned, with the rotation axis horizontal. Similar to the familiarisation phase, the target emergence was followed the predictable path: the frog appeared from the bottom and the cow from the top. In both phases, each target was briefly projected outward via a smooth, continuous pop-out animation before retracting to a stationary position. A brief transition screen was shown between the familiarisation and test phases, showing a small, animated animal character centred on a dark background, which marked a pause sequence. This sequence could be manually continued by the experimenter by pressing the space bar.

Apparatus

The task was conducted in a rectangular cabin with lateral and posterior closed sides, leaving only the front open. A 24 inch computer monitor was placed 60 cm in front of a chair, with the closed wall of the cabin serving as a neutral background. Infants sat on their caregivers' laps and were oriented towards the monitor. The infant's gaze behaviour was recorded using a Tobii X120 eye tracker (120 Hz), which was mounted below the screen. In addition, a small web camera was positioned above the infant's head and recorded the experiment. The stimulus presentation and gaze data acquisition were managed through the native Tobii Studio software (Tobii Pro, 2022).

Prior to the test trials, eye tracker calibration was performed in Tobii Studio using a four-point calibration procedure. A neutral black background with cross-shaped markers located near the corners of the screen was used. A small, animated, coloured light moved between the points to attract the infant's attention. The calibration was controlled by the experimenter, with each point confirmed manually by pressing the space bar once a stable gaze was detected. Tobii Studio provided real-time feedback on gaze quality as a percentage score, which allowed for immediate assessment of calibration accuracy and infant positioning. Calibration was only accepted if a minimum quality threshold of 80% was reached to ensure reliable data for the subsequent test trials, which could not be repeated. If necessary, calibration was repeated, and the infant's seating position was adjusted accordingly. To gain the infant's attention during calibration, an animal-like sound was played rhythmically while the animated light moved between calibration points.

Procedure

Before the experiment began, parents were informed about the purpose and general procedure of the study and provided written consent for their infant's participation. The experiment began after successful calibration and consisted of six familiarisation trials and six test trials, which were started manually by the experimenter.

Each trial in the familiarisation and test phase followed an identical temporal structure, consisting of two half-sequences of approximately 6.5 sec each (see Fig 4.1). The trial began with the (i) array rotated from the front, fully occluded position through a 45° along its rotation axis (vertical in familiarisation and horizontal in test phase respectively) over 1.5 sec, revealing Target 1 (e.g., the frog) and it popped out for 1.5 sec. (ii) As it reached 45°, the target retracted back in and the array rotated backwards over 1.5 sec and during this phase, Target 2 on the opposite side remained fully covered (target occlusion); (iii) After Target 1 retracted and the array entered a stationary state (full occlusion phase) where both targets were completely hidden from view for 2 sec. This exact sequence was then repeated in the opposite direction, which revealed Target 2 and occluded Target 1 (target occlusion), with identical timing: 1.5 sec of rotation, 1.5 sec of pop-out, 1.5 sec of return rotation, and 2 seconds of full occlusion phase (stationary). Thus, each trial consisted of two target occlusion events (one per target) and two full occlusion events, with a total trial duration of approximately 13 sec.

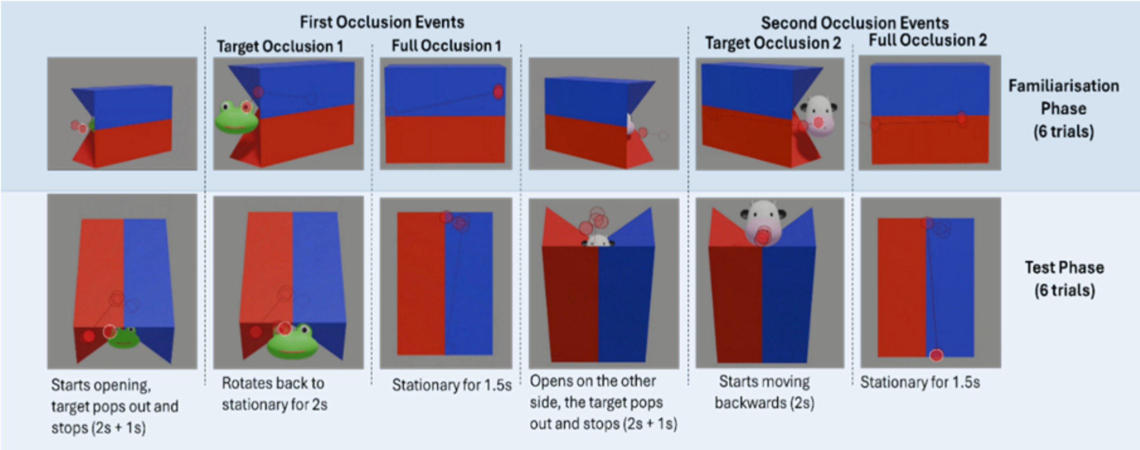

Figure 4.1: Occlusion events and phases of the prediction task. Representation of the timing and sequences of the targets' presentation and occlusion events during one trial. There were two occlusion events: full occlusion (both targets are occluded) and target occlusion (only one target is occluded) in each of the phase.

4.3.4 Bayley Scales of Toddler and Infant Development III

To obtain information regarding infants' motoric development, we conducted the Bayley Scales of Toddler and Infant Development III (Reuner et al., 2014) using the gross motor development subscales. The gross motor scale primarily assesses the movements of the limbs and torso with respect to static positioning and dynamic movement. For the setup, a small table was used that provided sufficient space for the interaction, along with two chairs for one of the parents and the experimenter. Infants were seated on their parents' laps. Before the assessment, parents were instructed to avoid interaction or eye contact in order not to distract the infant. They were also asked not to assist the infant during the procedure. The materials used during the assessment included standardised test sheets listing the items for each subtest (fine motor skills, gross motor skills and cognitive skills), a pen for scoring and the standardised toys and objects specified in the Bayley manual. A video camera was set up to record the assessment, allowing for later review and item correction to ensure that the procedure was carried out accurately. Additionally, the materials were cleaned with disinfectants after each session. Before the assessment began, it was crucial to establish a playful environment in which the infant could participate actively. The assessment followed standardised evaluation rules. Infants were awarded one point for each item if they performed the behaviour successfully, or zero points if they did not demonstrate the behaviour. The total number of points obtained across all completed items formed the final raw score for each subtest. Based on the infant's age, a defined starting point was selected for item presentation. If the infant did not complete the initial item, testing resumed at an earlier entry level appropriate for earlier developmental stages. The assessment continued until the infant failed to receive a point on five consecutive items, at which point the subtest was discontinued. Based on the raw item scores, total scores were created for gross motor.

4.4 Data Coding and Scoring

4.4.1 Visual Prediction Task

Time of interest (TOI)

Infants' gaze behaviour was analysed within two predefined time windows, or Time of Interest (TOIs), which allowed us to examine their ability to anticipate the future position of a moving object temporally. We analysed whether infants' gazes landed in certain areas of interest (AOIs; see section below 4.4.1) in these defined TOIs. The first window, *the target occlusion period*, encompassed the moment when the target that was about to be hidden popped back inside the occluder, a 0.5s stationary phase, followed by the 1.5s backward motion of the visible object during which the other target was occluded. This period, therefore, captured a total of 2 s during which the infant could potentially anticipate the hidden target's reappearance while still receiving motion cues from the visible object. Because the movement of the visible target may guide attention, anticipatory looks during this period represent a relatively less conservative measure of predictive behaviour. The second window, *the full occlusion period*, corresponded to the 1.5-s interval in which both objects were simultaneously occluded. During this interval, infants had no access to visible motion cues, and any gaze shifts toward the expected reappearance location therefore reflected a more conservative and cognitively demanding form of prediction. For each of the defined time zones, infants observed 24 occlusion events: 12 during familiarisation and 12 during test trials, with each trial consisting of 2 occlusion events for each target. Consequently, infants could contribute a maximum of 24 data points during the experimental session for each time zone.

Area of Interest (AOI)

In the familiarisation trials, target AOIs were created on the left and the right side of the screen where the target is anticipated to appear. In the test trials, the AOIs were created in the same way as the AOIs during the familiarisation trials, with the exception that target AOIs were placed up and down. According to Gredebäck and von Hofsten (2004), only occlusion events in which infants tracked the targets both before and immediately after occlusion were included in the analysis. Fixations were defined as having a minimum radius of 35 pixels and a minimum duration of 200 ms (Gredebäck & von Hofsten, 2004). To determine whether infants visually predicted the future position of the targets during the occlusion events, we first dichotomised gazes as either predictive or reactive. A gaze was considered predictive if the infant fixated the AOI in which the target was expected to emerge during either the target occlusion or the full occlusion period, before the target became visible. In contrast, a gaze was considered reactive if it fell on the AOI in which the target had previously been visible at the moment of its reappearance. The definition of predictive versus reactive AOIs depended on the direction of object motion: for example, if a target had last appeared on the left, the right AOI was designated as predictive and the left as reactive, and this logic was mirrored when the target last appeared on the right, or in the vertical orientation during the test trials. For each occlusion event, a predictive fixation was coded as present (1) if the infant met the minimum fixation criteria within the predictive AOI during the relevant time-of-interest (TOI), and absent (0) otherwise. A trial was considered valid only if the infant fixated the reactive AOI upon the target's reappearance, ensuring that the infant was actively tracking the object trajectory. Infants were included in the final analysis if more than 50% of their occlusion events met these validity criteria.

Calculating Predictive Looks

For each trial, fixation duration within each AOI was first assessed. If a fixation met the minimum duration criterion, the trial received a score of 1 for that AOI; trials in which no qualifying fixation occurred were scored as 0. Trial validity was determined by the presence of a fixation to the reactive AOI at the time of target reappearance. Only valid trials were included in subsequent analyses. For each infant, a Prediction Rate (PR) was calculated separately for each AOI and each TOI by dividing the number of predictive looks by the total number of valid trials and multiplying by 100. This measure indexed the proportion of occlusion events in which infants anticipated the future position of the target, allowing assessment of visual prediction under conditions of partial and full occlusion.

4.4.2 MR Task

Following Schwarzer et al. (2022) and similar to the analysis used in Study 1 of infant MR task, we averaged the infants' looking times for each test video separately, which included three videos of the habituation objects and three videos of the mirror objects at the previously unseen angles. We then computed the difference between the average looking time at the mirror object video and the average looking time at the familiar habituation object video. A difference of zero indicated that the infant could not distinguish between the familiar, habituation object presented in a novel rotation angle and the corresponding mirror object. A negative difference indicated longer looking times to the familiar object, while a positive difference indicated longer looking times to the mirror object. We focused solely on the magnitude of the difference between the looking durations. These scores served as a measure to index the ability to distinguish between the mirror and the familiar object, representing a fundamental aspect of MR.

4.5 Results

4.5.1 Visual Prediction Task

Prediction rates were normally distributed (all $p > .24$); therefore, parametric tests were conducted. A repeated-measures analysis of covariance (ANCOVA) was performed with phase (familiarization vs. test) and occlusion event (target occlusion vs. full occlusion) as within-subject factors, sex as a between-subject factor, and age as a covariate. There were no significant main effects of occlusion, $F(1, 20) = 0.25$, $p = .61$, $\eta_p^2 = .01$, or phase, $F(1, 20) = 0.17$, $p = .67$, $\eta_p^2 = .009$. Sex also did not have a significant main effect, $F(1, 20) = 0.37$, $p = .54$, $\eta_p^2 = .01$, nor did age, $F(1, 20) = 0.15$, $p = .70$, $\eta_p^2 = .007$. No significant interaction effects were observed. Descriptive statistics are provided in Table 4.1.

Table 4.1: Descriptive statistics of prediction rates in occlusion events in both phases

Occlusion	Phase	N	Mean(%)	SD
Target	Familiarisation	23	46.41	20.02
	Test	23	37.54	19.73
Full	Familiarisation	23	45.61	23.61
	Test	23	30.54	14.66

To investigate the influence of gross motor skills on predictive performance, participants were divided into high and low motor skill groups using a median split. Following Kubicek et al. (2017b), who reported crawlers outperformed non-crawlers during test trials but not during familiarization trials and given that we did not find any differences in the test and familiarisation phase in our previous repeated-measures ANCOVA, two separate repeated-measures ANCOVAs were conducted examining motor ability within each phase (test and fam) separately, with occlusion type (target, full) as the within-subject factor, motor skill group (high, low) as the between-subject factor, and age as a covariate.

For the familiarisation phase, the repeated-measures ANCOVA revealed no significant main effect of motor group, $F(1, 20) < 1$, $p = .99$, $\eta_p^2 < .01$, no significant main effect of occlusion type, $F(1, 20) = 0.38$, $p = .54$, $\eta_p^2 = .01$, and no significant

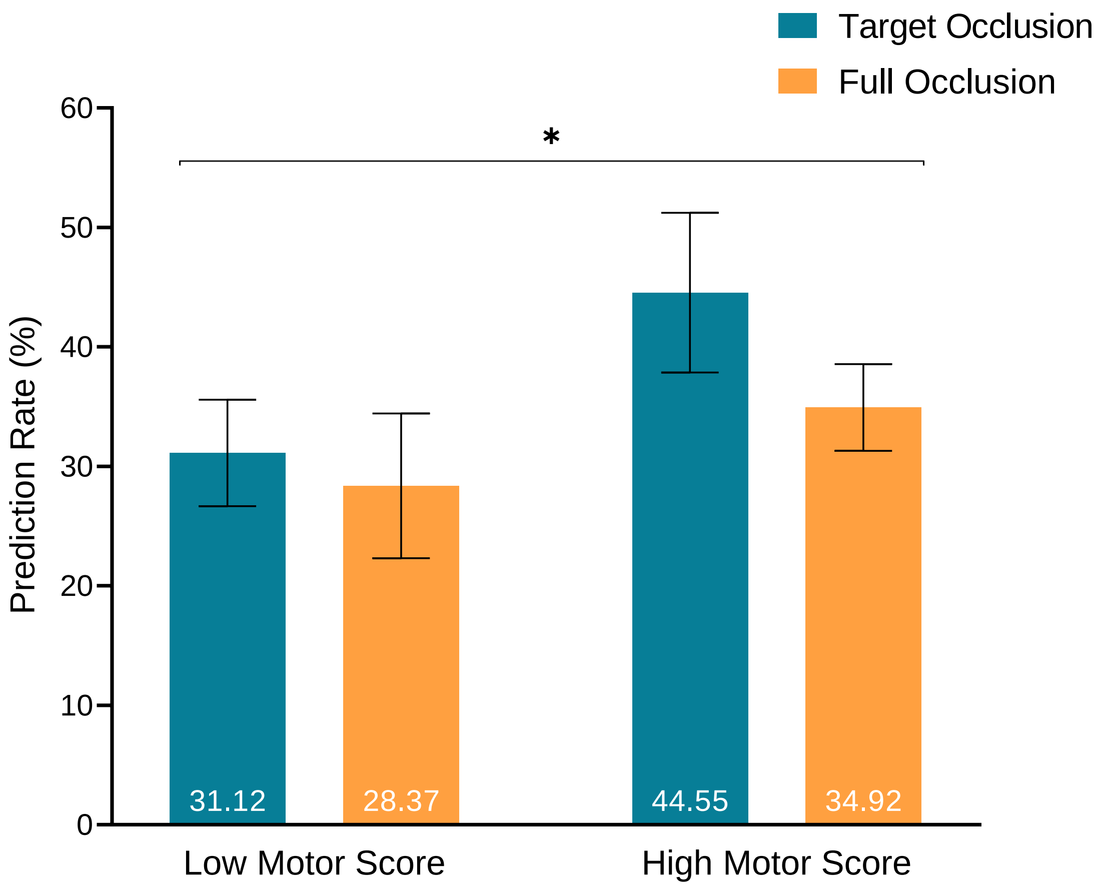

Figure 4.2: Prediction rates for target and full occlusion events during test phase in high and low motor score groups. Data represents means and error bars represent standard error of the mean. $^{*}p < .05$.

interaction between occlusion type and motor group, $F(1, 20) = 0.39$, $p = .53$, $\eta_p^2 = .02$.

For the test phase, no significant main effect of occlusion type was found, $F(1, 20) = 0.04$, $p = .84$, $\eta_p^2 = .002$, and the interaction between occlusion type and motor group was non-significant, $F(1, 20) = 0.33$, $p = .56$, $\eta_p^2 = .01$. However, a significant main effect of motor group was observed, $F(1, 20) = 4.19$, $p = .05$, $\eta_p^2 = .17$, indicating that infants in the high motor skill group demonstrated significantly higher predictive performance than those in the low motor skill group, regardless of occlusion condition (see Fig 4.2).

4.5.2 MR Task

A one-sample t-test indicated that the difference scores were significantly above chance, $t(17) = 5.03$, $p < .001$. Preliminary analyses were conducted using an ANCOVA with sex and randomization of habituation object as fixed factors, age as a covariate, and difference scores as the dependent variable. There were no significant main effects of sex, $F(1, 13) = 0.007$, $p = .93$, or of randomization, $F(1, 13) = 0.87$, $p = .36$, on the difference scores.

To examine the influence of gross motor skills, participants were divided into high and low motor skill groups using a median split of the standard Bayley gross motor score.

An independent-samples t-test revealed no significant difference between the high (M = 4.76) and low (M = 4.89) motor groups, $t(16) = -0.06$, $p = .95$.

4.5.3 Link Between MR and Prediction Ability

To further examine the relationship between MR and prediction ability, Pearson correlations were conducted between MR difference scores and prediction rates separately for each phase.

The results indicated no significant correlation between MR difference scores and prediction rates in the target occlusion condition, in both the familiarization phase, $r_p(15) = -0.21$, $p = .41$, and the test phase, $r_p(15) = -0.12$, $p = .63$. Similarly, no significant correlation was found between MR difference scores and prediction accuracy in the full occlusion condition, in both the familiarization phase, $r_p(15) = -0.45$, $p = .06$, and the test phase, $r_p(15) = -0.21$, $p = .41$.

Additionally, prediction rates were collapsed across both phases to derive an overall index of anticipatory looking ability, allowing examination of the general relationship between MR and predictive performance. However, no significant correlations were found between MR and either total target occlusion, $r_p(15) = 0.04$, $p = .87$, or total full occlusion, $r_p(15) = -0.29$, $p = .24$.

4.6 Discussion

The primary aim of this pilot study was to examine the development of 3D-MR in 9- to 12-month-old infants and its potential relationship with visual prediction abilities. To this end, we developed a screen-based task to measure predictive capacities. During the familiarisation phase, infants' prediction rates were approximately 45%; however, performance declined in the test phase, likely because changes in object orientation disrupted previously learned predictive strategies. The use of a screen-based paradigm, rather than a live setup, also represents a methodological departure from prior work (Kubicek et al., 2017b), potentially influencing infants' engagement and task performance.

Our results revealed a dissociation between 3D-MR and visual prediction. In accordance to the spatial typology Newcombe et al. (2013), predicting the reappearance of an occluded object relies on tracking inter-object spatial relations and motion dynamics in real time, whereas MR requires intra-object processing, involving the mental transformation of a single object to a novel viewpoint. For example, anticipating that a toy car will reemerge after passing under a sofa requires maintaining continuity of its trajectory, while imagining the car from a rotated perspective requires manipulating its structural features mentally. Although both tasks draw on 3D spatial representations, they differ in cognitive demands and processing dynamics, which may contribute to the lack of correlation observed between MR and predictive abilities in our sample.

Task-specific characteristics may further explain this dissociation. Despite being well-designed to target their respective mechanisms, the MR and predictive tasks differed in format, complexity, perceptual demands, and motivational salience. Predictive tasks require infants to anticipate outcomes in real time under conditions of uncertainty, whereas post-hoc measures provide full information about completed actions. Few studies have directly compared these approaches, but existing evidence suggests they rely on partially distinct mechanisms. Online predictions are often experience-dependent and emerge later in development (Cannon & Woodward, 2008; Falck-Ytter et al., 2006; Gredebäck & Melinder, 2010), while predictive gaze does not consistently align with post-hoc looking-time responses (Paulus, 2011). Supporting this, Daum et al. (2012) showed that 9-month-old infants exhibit divergent patterns across predictive gaze and looking-time measures: predictive gaze primarily reflected location-based anticipation, whereas looking-time responses reflected identity-based expectations. Across a broader age range, this dissociation persisted until around the third year, when convergence emerged, with both measures reflecting identity-related expectations. These findings suggest that post-hoc measures preferentially engage ventral stream processes for object identity, whereas online predictive measures rely more on dorsal stream mechanisms supporting spatial and action-related computations. This distinction aligns with our findings, indicating that the absence of a correlation between MR and predictive tracking may stem from differences in representational demands and temporal processing, rather than an absence of conceptual linkage between transformational and predictive abilities. The present study also examined the role of motor development in these processes. Consistent with prior research (Kubicek et al., 2017b), infants with more advanced gross motor skills performed better on predictive tasks. No similar association was observed for MR, potentially due to the small sample size. These results support the notion that self-produced motor experience fosters spatial cognition by enhancing visual exploration, proprioception, and perspective-taking. Nevertheless, despite parallel motor-related improvements, 3D-MR and predictive abilities remained uncorrelated in this sample, underscoring the possible complexity of the mechanisms linking these processes. It is also important to note the limitations imposed by our small sample size. Low statistical power reduces the likelihood of detecting true associations, particularly in an age range characterised by high developmental variability. Thus, the current findings should be interpreted with caution, and replication with larger cohorts is necessary to clarify potential relationships between 3D-MR and predictive abilities in infancy.

4.7 Conclusion

Taken together, our findings contribute to an emerging picture in which MR and predictive tracking, while both reliant on spatial representations, appear to rely on partially distinct cognitive mechanisms in infancy. The lack of correlation observed may reflect differences in the type of representational information recruited (intra-object vs. inter-object), the temporal dynamics of processing, and task-specific constraints, rather than a complete developmental dissociation. Future research that combines MR and predictive measures within unified paradigms and considers the role of motor experience will be critical for elucidating how infants coordinate multiple forms of spatial cognition. A deeper understanding of these processes has broad implications, from early goal-directed action and problem-solving to the foundations of later STEM-related skills.

Chapter 5

General Discussion

Infancy and the preschool years are foundational periods during which essential cognitive and motor functions are established, shaping human development across the lifespan (Adolph, 2008; Von Hofsten, 2004). From very early on, infants interact with 3D objects that move, rotate, disappear, and reappear, and they flexibly update their understanding of the environment across space and time (Beard et al., 1971; Von Hofsten, 1986). Early motor experiences, particularly the onset of crawling, fundamentally alter how infants perceive the 3D environment and act within it by initiating developmental pathways that shape spatial cognitive abilities (Campos et al., 2000).

Keeping this in mind, the overarching goal of this dissertation was to advance understanding of the development of 3D-MR from infancy to the preschool years, along with the potential role of motor experience in its development. Across three experimental studies employing both longitudinal and cross-sectional designs, the present work (i) elucidated the developmental trajectory of 3D-MR from infancy to preschool age through a longitudinal design in Study 1 and cross-sectionally in preschoolers in Study 2 (ii) examined the role of motor development in supporting 3D-MR across both stages, as assessed longitudinally in Study 1 and cross-sectionally in preschoolers in Study 2 and in infancy in Study 3, and (iii) investigated whether intra-object spatial processing, as indexed by MR, is related to inter-object processing, as indexed by predictive abilities, during infancy in Study 3. Across all three studies, we created and employed novel age-appropriate yet conceptually comparable 3D tasks.

This chapter summarises the findings of the three studies, reflects on and discusses four main contributions to the broader literature. Finally, outlining directions for future research, implications and conclusions.

5.1 Development of 3D-MR from Infancy to Preschool Age

A central and primary contribution of this dissertation is the demonstration of the development of 3D-MR from infancy to the preschool years, evidenced by both longitudinal and cross-sectional studies using age-adjusted tasks. Importantly, the foundations of 3D-MR established in infancy continue to be related to 3D-MR performance throughout the preschool years, suggesting signs of developmental continuity. Early motor experience, such as crawling ability and concurrent motor skills (addressed in detail in Section 5.3), contributes to these outcomes.

Study 1 demonstrated longitudinal evidence between 9-month-old infants' 3D-MR performance and later 3D-MR competence during the ages of 4 to 6. This finding extends previous work by Lauer and Lourenco (2016), who demonstrated a developmental link between 2D-MR at these two stages. Importantly, the present association is characterised by a relatively large correlation, suggesting that early MR abilities play a substantial role in the development of later MR skills, including those involving 3D stimuli. This is particularly interesting because of the evidence that MR is linked to later academic success and STEM fields (Wai et al., 2009). While many training effects that are demonstrated in cross-sectional studies of preschoolers show improvement of MR (Fernández-Méndez et al., 2018; Hawes et al., 2015a), such studies cannot establish whether early individual differences persist over time. The present longitudinal evidence, therefore, addresses a major gap in the literature, demonstrating that early 3D-MR performance is not merely a transient perceptual phenomenon but is meaningfully related to later spatial competence.

Additionally, the longitudinal findings support the developmental continuity account proposed by Frick et al. (2014). According to their review, apparent inconsistencies in the literature suggest that while infants show early evidence of MR, preschool-aged children, particularly around 3 to 4 years, often perform at a chance level. By age 5, however, children reliably perform above chance, suggesting a re-emergence of MR abilities. This pattern could be interpreted as a temporary loss followed by recovery, which would contradict assumptions of continuity in cognitive development. Such an interpretation, however, is unlikely. It is implausible that infants possess more advanced MR abilities than preschoolers, only for these abilities to disappear and later reappear. Instead, these inconsistencies are more plausibly explained by differences in task demands and methodological approaches rather than genuine developmental discontinuity. Tasks used with infants often rely on implicit measures, whereas tasks administered to preschoolers typically require explicit responses, greater attentional control, and additional executive or linguistic resources. Thus, the observed dip in performance around 4 years likely reflects task-related constraints rather than a loss of MR competence. Although the present study did not assess children between 3 and 4 years of age, our findings contribute to the growing body of evidence supporting developmental continuity in MR, particularly when using age-adjusted tasks.

Complementing the longitudinal findings, Study 2 further supported the cross-sectional development of 3D-MR, showing a developmental trend with older preschoolers outperforming younger children on the age-adjusted block task. This aligns with the previous finding of Hawes et al. (2015a) on 3D-MR and also strengthens the finding that the development of 3D-MR with age, similar to studies showing this for 2D-MR.

Together, these findings extend the existing accounts that view MR as a skill that primarily emerges during early childhood and instead support the view that its foundations are established within the first year of life and can indeed predict later MR performance in preschool age.

5.2 Methodological Contribution and Use of Age-Adjusted 3D-MR Tasks

The second contribution is the successful development of valid age-adjusted 3D-MR tasks in preschoolers. Drawing on established infant paradigms of 3D-MR (Gerhard-Samunda et al., 2021) and existing 2D-MR tasks for preschoolers, such as the BiRT (Quaiser-Pohl et al., 2010), the present work introduces conceptually aligned tasks that allow for systematic investigation of 3D-MR development across early childhood. By maintaining conceptual continuity while adjusting task demands to children's developmental capacities, these tasks enabled the examination of both longitudinal continuity from infancy into the preschool period (Study 1) and developmental change within the preschool years (Study 2).

The task design was guided by two primary considerations: the mode of presentation and the incorporation of angular disparity. In Study 1, a screen-based task was employed that closely resembled the infant habituation paradigm used by Gerhard-Samunda et al. (2021). This approach followed children longitudinally from infancy into the preschool period by using the same stimuli to maintain consistency in perceptual format and temporal dynamics while minimising confounds at both time points. In Study 2, we utilised tangible objects similar to those used by Kelch et al. (2021), while adapting the task paradigm and the logic was inspired by the Ghost task (Frick et al., 2013b) to capture a more real-world interaction with perception and action. Angular disparity is a defining feature of MR, yet prior research with preschoolers has largely relied on 2D stimuli to examine its effects (Frick et al., 2013a; Quaiser-Pohl et al., 2010). While these studies have demonstrated that young children can discriminate between rotated and mirrored images, they provide only limited insight into depth rotation. By contrast, the present preschool tasks employed 3D stimuli and varied the degree of angular disparity between target and mirror objects. Both the screen-based and the tangible block tasks revealed clear angular disparity effects, indicating that increasing rotation angles were associated with decreased performance or increased processing demands. These findings extend earlier infant work by Gerhard and Schwarzer (2018), who demonstrated sensitivity to angular disparity using screen-based 3D paradigms. The present results show that this sensitivity is preserved and further differentiated in preschool-aged children when assessed using age-appropriate, explicit tasks. To the best of current knowledge, this dissertation provides the first evidence of angular disparity effects in preschoolers using 3D stimuli, establishing angular disparity as a sensitive index of 3D-MR efficiency in this age group.

Consistent with previous findings by Frick et al. (2013b), both tasks revealed significant age-related improvements in performance, with children performing above chance levels across conditions. Notably, the tangible block task was sensitive to differences between younger and older preschoolers, suggesting that this task is well-suited to capturing developmental change within this age range. The development of our novel tasks extends the findings of 3D-MR from previously used infant tasks by Moore and Johnson (2008) and later by Schwarzer et al. (2013a), who employed screen-based habituation tasks using the Shepard-Metzler 3D object, demonstrated significant results of 3D-MR in infancy to preschoolers. This adds to the existing 3D tasks by the Vandenberg and Kuse (1978) test, which has only been used with older preschoolers (Rüsseler et al., 2005), and the action-based task by Hawes et al. (2015a). More interestingly, the correlations between performance on the BiRT and the 3D-MR tasks in both Studies 1 and 2 suggest overlapping developmental pathways for 2D and 3D-MR in preschoolers. This finding aligns with prior work by Hawes and colleagues (2015a), who reported links between 2D and 3D spatial abilities, suggesting that while the two forms share underlying cognitive mechanisms, motor engagement may facilitate performance in younger children. While infant studies have demonstrated MR using both 2D and 3D stimuli, no previous research has examined the relationship between these abilities using correlational approaches. In preschoolers, the association between 2D and 3D-MR may be particularly strong, as this developmental period is marked by increased exposure to spatial language (e.g., up, down, left, right) and formal spatial concepts. Hence, one of the main contributions of this dissertation is the focus on understanding the development of MR in depth and extending the findings of 2D.

From a cognitive perspective, these findings are consistent with accounts of Jäncke et al. (2001), stating that MR has three prerequisites. First, a visually perceived object has to be mentally represented. Second, the spatial features of the mental representation have to be uncoupled from its other features. Third, the spatial features have to be processed. Concerning this framework, the same underlying mental processes might apply to succeed in both our tasks. Additionally, in the Block task, children must learn about the relationship between 3D objects and 2D apertures, how an object and its projective properties change during rotation, and how to move the object to attain specific object orientations. As the task involves a decision component, the child may temporarily maintain a mental representation of the objects in working memory while simultaneously attending to the aperture. This may indicate that working memory contributes to successful task performance (Ebert et al., 2025). Furthermore, they must have the ability to also inhibit their wrong impulses when there is more than one alternative action. Keeping this interplay between perception and action, our task suggested evidence that the development of both processes occurs in tandem, as we didn't find any differences between the accuracies of them, also consistent with the findings of Krüger and Krist (2009).

Taken together, these findings underscore the importance of employing age-adjusted, conceptually aligned tasks and highlight the value of studying MR using 3D stimuli to understand its emergence and development across early childhood.

5.3 Role of Motor Development in 3D-MR

The third contribution lies in demonstrating a robust and enduring link between motor development and 3D-MR from infancy through the preschool years across the first two studies. In infancy, self-produced locomotion, particularly crawling, was associated with enhanced performance on 3D-MR tasks, as evidenced by Gerhard-Samunda et al. (2021). Importantly, in Study 1, we extended this finding by demonstrating that crawling ability continued to be associated and predict individual differences in 3D-MR performance during the preschool years, indicating that the motor–spatial cognition link extends well beyond infancy. Specifically, it was shown that a 9-month-old crawling infant performed better at MR at preschool age compared to a non-crawling infant, indicating a developmental continuity.

In addition to this longitudinal finding, Studies 1 and 2 revealed cross-sectional associations between motor skills and 3D-MR competence in preschoolers. As most prior studies linking motor skills and MR in preschoolers have relied on 2D tasks (Jansen & Heil, 2010), the present findings demonstrate that these associations also hold for 3D-MR tasks. These studies are among the first to demonstrate consistent links between motor skills and 3D-MR across multiple samples of preschool children. Notably, the motor–spatial association observed in infancy appears to remain present during the preschool years, suggesting developmental stability in the coupling between action and spatial transformation.

Study 2 further refined this picture by elucidating the differential contributions of gross and fine motor skills to 3D-MR performance in preschoolers. Whereas Study

1 established the presence of a general motor-MR link, Study 2 showed the nuanced relationship between gross and fine motor skills in preschoolers. The fact that fine motor skills predict 3D-MR (in the Block task) only in older preschoolers also emphasises how our task itself, which had the manual fitting involved motor engagement. This also suggests how such block training or hands-on puzzle play can form the basis or improve spatial representation. Together, these results align with embodied theories of cognition, which posit that sensorimotor experiences provide essential input for building abstract mental representations and also that ongoing motor engagement continues to support spatial transformation.

The strong association between motor performance and task success reinforces the idea that perception and action develop in tandem and are jointly shaped by the developing motor system (Frick & Möhring, 2016). The act of manipulating tangible objects may provide children with embodied feedback about spatial relationships, thereby enhancing their mental transformation abilities. This is consistent with theories of embodied cognition, which suggest that spatial reasoning is rooted in perceptual–motor experiences (Ebersbach & Krüger, 2017; Krüger et al., 2014a). From a developmental systems perspective, self-produced action, such as crawling or object manipulation, may recalibrate spatial reference frames and refine internal representations, as suggested by Soska et al. (2010) in the context of occlusion completion. The longitudinal gains in MR following the onset of crawling are consistent with the idea of reciprocal influences, whereby action supports mental simulation, which in turn may be further refined through continued practice and experience.

Study 3 provided partial support for these conclusions. While a significant association was found between gross motor skills and prediction abilities, replicating findings reported by Kubicek et al. (2017a), no reliable link between motor skills and MR was observed in this pilot study. This null finding should be interpreted cautiously, given the limited sample size and exploratory nature of the study. It is also possible that differences in task demands or measurement sensitivity contributed to the absence of a detectable motor-MR association.

Taken together, the findings of this dissertation provide strong support for embodied cognition and Piagetian accounts of spatial development, which posit that spatial knowledge emerges through action. Crawling infants may be exposed to more systematic changes in viewpoints, object orientations, and spatial relations, that non-crawling infants, enabling the integration of visual, proprioceptive, and tactile information (De Klerk et al., 2016). Over time, these embodied experiences appear to scaffold the internalisation of spatial transformations, giving rise to increasingly flexible and abstract mental representations. By demonstrating both longitudinal and cross-sectional links between motor development and 3D-MR, the present work provides the first findings with 3D stimuli and highlights the central role of action in shaping spatial cognition across early development.

5.4 Linking Inter-object (Prediction) and Intra-object (MR) Processing

Beyond the role of motor experience, the present work sheds light on the relationship between inter-object processing (predicting object motion and reappearance) and intra-object processing (3D-MR) in infancy. While previous research has largely investigated predictive processing (Adam et al., 2025) and MR (Moore et al., 2024) in isolation or at later developmental stages, the present studies aimed to bridge this gap by assessing their relationship in infancy. Contrary to expectations, our pilot study revealed no association between infants' MR ability and their capacity to predict object motion in space in the present sample. This null finding may not imply that predictive processing and MR are unrelated; rather, it may suggest that these abilities may not be captured equally by the paradigms employed or may rely on partially distinct cognitive demands at this developmental stage.

The methodological distinction is critical. MR was assessed using a habituation paradigms which rely on infants' differential looking to familiar versus novel stimuli, providing relatively direct evidence of perceptual discrimination (Fantz, 1956, 1964). In contrast, prediction of object motion requires online processing, involving the continuous updating of object representations across time and space. In this respect, predictive tracking more closely resembles VoE paradigms, which measure infants' longer looking times as surprise, an inference that has been subject to extensive theoretical critique (Bogartz et al., 2000; Cashon & Cohen, 2000; Haith, 1998; Moore & Cocas, 2006). As Paulus et al. (2011) notes, although both approaches rely on looking-time measures, they tap into different underlying processes. Thus, the lack of association observed here may reflect differences in task demands and temporal dynamics, rather than the absence of a conceptual link between prediction and MR. Additionally, Pedrett et al. (2020) also showed a lack of correlation between looking times and predictive gazes in the eye tracking task with toddlers.

Further insight into the apparent dissociation between predictive and post-hoc measures of infants' expectations comes from Daum et al. (2012), who directly compared online predictive gaze with post-hoc looking-time measures in infants' understanding of goal-directed actions. In their first experiment, 9-month-old infants showed divergent patterns across the two measures: while looking-time responses reflected identity-based expectations about action outcomes, predictive gaze primarily indexed location-based anticipation, if any prediction was observed at all. Extending this work across a broader age range, their second experiment demonstrated that this dissociation persists throughout the first three years of life, with convergence between the two measures only emerging after the third birthday, when both began to reflect identity-related expectations. They interpret this developmental dissociation as evidence for partially distinct underlying mechanisms, suggesting that post-hoc measures may preferentially engage ventral stream processes related to object identity, whereas online predictive measures may rely more strongly on dorsal stream mechanisms supporting spatial and action-related processing. This distinction resonates with the present findings, in that the absence of an association between MR and predictive object tracking in infancy may reflect differences in the type of representational information and processing dynamics recruited by the respective paradigms, rather than a lack of conceptual relatedness between predictive and transformational abilities. This is in line with the recent meta-analysis suggesting that infants' looking responses are influenced by conceptual and perceptual novelty independently (Kunin et al., 2024). Within the predictive processing framework, both anticipating object motion and mentally rotating objects can be conceptualised as forms of internal simulation. In both cases, infants must generate predictions about how objects will change across time or viewpoint. The present findings, therefore, set the basis for further studies on this relation.

Finally, motor skills emerged as a modulating factor in the relationship between prediction, underscoring the role of embodied experience. Through self-produced locomotion and active exploration, infants encounter objects that disappear, reappear, rotate, and change perspective. These experiences may simultaneously strengthen predictive tracking and mental transformation abilities, providing a shared developmental foundation for inter-object and intra-object processing.

Taken together, the present results contribute to a more integrated view of spatial cognition in infancy. While methodological differences may obscure their association under certain conditions, converging evidence supports the idea that prediction, perception, and action jointly shape the emergence of spatial cognition early in life.

5.5 Implications for Theory, Education, and Intervention

The findings of this dissertation have important theoretical, educational, clinical, and practical implications. Theoretically, they support a developmental systems perspective in which spatial cognition emerges through the dynamic interaction of perception, action, and prediction. MR is reconceptualised not as a purely abstract skill, but as an embodied and developmentally continuous ability grounded in early object-directed behaviour. The observed link between 3D-MR and motor skills underscores that motor activity is not merely a behavioural expression of spatial cognition but an active contributor to its development, aligning with embodied cognition frameworks which posit that cognitive processes are grounded in sensory and motor systems (Von Hofsten, 2009).

From an educational perspective, these findings highlight infancy and early childhood as sensitive periods for spatial development. By illuminating how perceptual, cognitive, and motor processes interact in early life, we can better understand the foundations of spatial reasoning and its role in later academic, STEM fields and real-world problem-solving contexts (Fanari et al., 2019; Geer et al., 2019). These findings further extend to early literacy, as preschoolers learning to distinguish mirror-image letters (e.g., d/b, p/q) rely directly on MR and spatial perception (Ahr et al., 2016), positioning early spatial development as a transversal competency with consequences across mathematical, scientific, and literacy domains. Exploratory play, such as manipulating blocks (LEGO), rotating objects, solving fitting tasks (puzzles), sculpting, and movement-based challenges, directly supports spatial reasoning while also fostering problem-solving, logical reasoning, and perspective-taking (Cortes et al., 2022; Dinehart & Manfra, 2013; Frick & Möhring, 2016; Morawietz et al., 2024). Targeted MR games (De Lisi & Wolford, 2002) can yield measurable gains even in young preschoolers, for girls and boys alike, and such interventions are low-cost, adaptable, and promote broader competence across school and everyday life (Serino & Ossmy, 2025; Weber et al., 2024). Equitable access to such experiences is critical, as disparities in high-quality spatial and motor play can emerge early, shaped by gendered expectations (cars being more male-oriented than dolls for females, home routines, and cultural attitudes (Ebert et al., 2024; Schneider, 2025).

Given the interdependence of motor skills and MR, clinically, early motor delays may have downstream consequences for spatial cognition. Identifying and supporting children with reduced motor opportunities through early interventions targeting motor development may have cascading benefits for spatial cognition (Campos et al., 2009). Motor skill training programs, such as those involving manual object exploration or gross motor play, have shown promising effects on improving spatial abilities in preschool children (Morawietz et al., 2024; Oudgenoeg-Paz et al., 2015; Yee et al., 2013). These interventions capitalise on the embodied nature of cognition, fostering active learning through movement and manipulation. Moreover, integrating motor activities into preschool curricula can support spatial reasoning and prepare children for later academic challenges, particularly in STEM domains where spatial skills are critical (Uttal et al., 2013). For instance, block play, drawing, and building activities encourage both fine motor coordination and spatial visualisation, promoting the development of MR.

5.6 Limitations and Future Directions

The major limitation of the present dissertation is the relatively small sample size. In Study 1, the longitudinal sample was reduced by approximately 50%, resulting in limited statistical power. Although the longitudinal design provides important evidence for developmental continuity in 3D-MR, the reduced sample size constrains the generalisability of the findings of the link between crawling ability and preschool 3D-MR and limits the ability to detect smaller developmental effects. Similarly, in Study 2, statistical power was low in the final regression model, further restricting the conclusions that can be generalised.

A further methodological limitation is the differences in response formats and measurement indices across developmental stages in Study 1. In infancy, 3D-MR was assessed using looking-time measures and a differential looking index, whereas at preschool age, performance was evaluated using accuracy-based outcomes. Although identical stimuli were used at both time points, these indices still have a chance to capture different aspects of behaviour and may also partially confound with distinct underlying processes. Nevertheless, the present study revealed stronger longitudinal associations than those reported in previous work (Lauer & Lourenco, 2016), because it employed similar stimuli and age-adjusted tasks. This finding reinforces the idea that greater measurement consistency across developmental stages could further strengthen longitudinal inferences. In this regard, developing paradigms that maintain comparable response indices across ages, such as the eye-movement–based approach introduced by Beckner et al. (2023a), and applying them in longitudinal investigations would offer a more controlled framework for studying MR. Using the same eye-movement parameters as the primary index of MR across development may help reduce methodological variability and provide clearer insight into developmental continuity.

Finally, although the dissertation highlights links between motor development and spatial cognition, the assessment of motor experience was always categorical or binary. Motor abilities were measured at discrete time points and primarily categorised in terms of skill presence or level, rather than as a continuous, cumulative history of motor engagement. This approach may overlook more nuanced aspects of motor experience, such as duration, variability, and context of locomotor activity (Burakevych et al., 2017).

Future research should first aim to address limitations related to sample size and statistical power. Larger longitudinal samples with extended follow-up periods are needed to clarify how early 3D-MR abilities relate to spatial cognition later in childhood and adolescence. Such designs would allow for more precise modelling of developmental trajectories and increase confidence in the generalisability of the findings. Multi-site collaborations may be particularly valuable in achieving sufficiently powered developmental samples.

Future work should also prioritise the development and use of more comparable measurement approaches across infancy and early childhood. Where possible, employing similar response formats or indices across time points would allow for clearer interpretations of developmental change rather than differences attributable to task demands. This approach has been successfully implemented in research on executive functioning, where age-appropriate adaptations of a common measure are used to track developmental continuity (Fiske et al., 2025). Applying similar strategies to 3D-MR research or adapting tasks like the staircase eye-tracking paradigm (Beckner et al., 2023a) to older children would strengthen longitudinal inferences.

In addition, future studies should conceptualise motor experience as a graded and longitudinal variable rather than relying on dichotomous classifications such as crawlers versus non-crawlers. Building on evidence from literature for more fine-grained assessments of motor history, capturing duration, diversity, and context of locomotor activity, would allow for a more nuanced understanding of how motor experience supports spatial cognition over time (Bai & Bertenthal, 1992; Jenni et al., 2013). Future studies should employ experimental and training-based designs that directly manipulate motor experience. For example, interventions that systematically vary opportunities for locomotion, object manipulation, or spatial exploration could provide stronger evidence regarding the causal role of motor development in shaping emerging MR abilities (Morawietz et al., 2024). Longitudinal intervention studies would be especially informative in determining whether changes in motor experience precede and predict changes in spatial cognition across developmental stages. Integrating behavioural measures with eye-tracking (Franchak et al., 2011; Rodriguez et al., 2025) and neurophysiological methods such as EEG (Kucian et al., 2007), fMRI (Lambrey et al., 2012) could further elucidate the neural mechanisms linking locomotor activity, attentional processes, and memory in the early development of object representation (Yee et al., 2013) and spatial prediction.

Finally, future research should extend these findings to applied and educational contexts. Investigating MR in classroom settings, particularly through the use of educational technologies and immersive tools such as virtual reality, may shed light on how spatial transformations are engaged in real-time learning environments (De Lisi & Wolford, 2002; Piri & Cagiltay, 2024). Such work could inform the development of targeted teaching materials and teacher training programs, especially in domains that rely heavily on spatial reasoning, including chemistry (e.g., molecular structures), biology (e.g., diagrammatic representations) (Stieff, 2007), and early literacy (e.g., letter discrimination such as b, d, p, and q) (Corballis & McLaren, 1984). Addressing the methodological and conceptual limitations identified in the present dissertation will be essential for translating foundational developmental findings into effective educational practice.

Chapter 6

Conclusion

In conclusion, this dissertation provides a comprehensive and integrative account of the development of 3D-MR from infancy through preschool years. By addressing key gaps in the literature concerning dimensionality, developmental continuity, motor experience, and predictive processing, it advances theoretical understanding of 3D-MR and underscores the embodied links between visuospatial abilities and motor skills.

Study 1 provides the one of the first evidence of a longitudinal link between 3D-MR performance in infants and 3D-MR competence in preschoolers. Importantly, it also elucidates the potential role of early self-produced locomotion by demonstrating that 9-month-old crawling infants who show better 3D-MR also perform better at 3D-MR tasks at 4 to 6 years of age. Study 2 further provides evidence of the nuanced relationship of fine and gross motor skills with 3D-MR performance at preschool age. While gross motor skills were linked to 3D-MR in younger preschoolers (4.6 to 5.5 years of age), fine motor skills were associated with 3D-MR performance in older preschoolers (5.6 to 6.5 years of age). Additionally, the key methodological contribution of this dissertation is the development of age-appropriate and conceptually comparable tasks that allow assessment of 3D-MR across both ages. Notably, these tasks are the first 3D-MR tasks that demonstrate an effect of angular disparity in preschool age, in tasks using both screen-based and tangible stimuli. In the pilot study 3, this dissertation further contributes to the literature by demonstrating a link between prediction ability (measured using a screen-based task) and self-produced locomotion in infants. Although no association between MR and prediction ability was observed in the current sample, likely due to the differences in task demands and measurement format, these findings lay important groundwork for our main study and for future research.

In sum, the central assumption was that motor skills, including self-produced locomotion in infancy as well as fine and gross motor abilities in the preschool period, constitute important factors that support 3D-MR development. The present findings are in line with this premise and extend them by suggesting 3D-MR development continuity, and by demonstrating that both infant self-produced locomotion and concurrent fine and gross motor proficiency are systematically associated with improvements in 3D-MR (see Fig 6.1). This supports embodied accounts of spatial cognition, highlighting the role of active exploration and motor engagement in refining mental representations of 3D space.

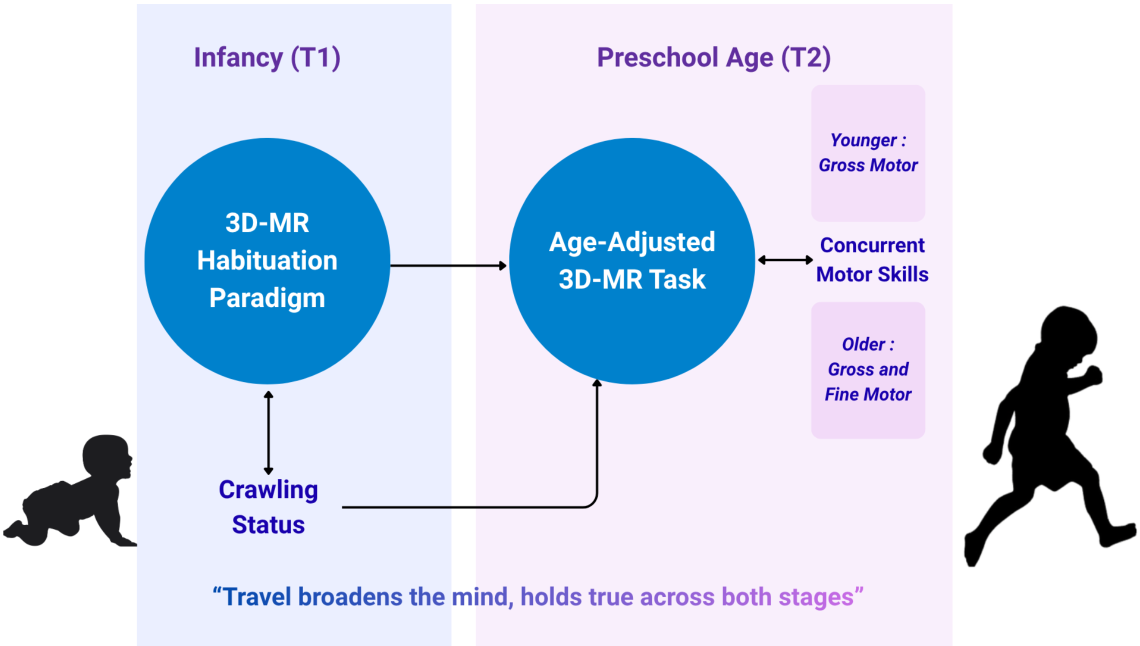

Figure 6.1: Overview of the links between 3D-MR and motor skills from infancy to preschool age.

Beyond its scientific contributions, this work offers valuable implications for educational practice and early intervention by emphasising that the foundations of spatial thinking are laid early, through action, exploration, and engagement with a 3D world. Overall, the findings offer a unified, developmentally grounded account of how 3D-MR emerges from early action and becomes increasingly refined across childhood. By demonstrating continuity from infancy to the preschool years and identifying systematic links between self-produced locomotion, motor proficiency, and spatial transformation abilities, the findings provide strong support for embodied theories of spatial cognition. In line with Campos et al. (2000), the present results suggest that active exploration continues to shape spatial thinking beyond infancy, affirming that, even in early childhood, travel quite literally broadens the mind.

References

Acredolo, L. P., Adams, A., & Goodwyn, S. W. (1984). The role of self-produced movement and visual tracking in infant spatial orientation. *Journal of Experimental Child Psychology*, *38*(2), 312–327. https://doi.org/10.1016/0022-0965(84)90128-0

Adam, M., Elsner, B., & Zmyj, N. (2025). Perspective matters in goal-predictive gaze shifts during action observation: Results from 6-, 9-, and 12-month-olds and adults. *Journal of experimental child psychology*, *249*, 106075. https://doi.org/10.1016/j.jecp.2024.106075

Adolph, K. E., & Robinson, S. R. (2015). *Motor development* (7th). Wiley.

Adolph, K. E. (2008). Learning to move. *Current directions in psychological science*, *17*(3), 213–218. https://doi.org/10.1111/j.1467-8721.2008.00577.x

Adolph, K. E., & Franchak, J. M. (2017). The development of motor behavior. *Wiley interdisciplinary reviews. Cognitive science*, *8*(1-2). https://doi.org/10.1002/wcs.1430

Adolph, K. E., & Hoch, J. E. (2019). Motor development: Embodied, embedded, enculturated, and enabling. *Annual Review of Psychology*, *70*, 141–164. https://doi.org/10.1146/annurev-psych-010418-102836

Ahr, E., Houdé, O., & Borst, G. (2016). Inhibition of the mirror generalization process in reading in school-aged children. *Journal of Experimental Child Psychology*, *145*, 157–165. https://doi.org/10.1016/j.jecp.2015.12.009

Amorim, M.-A., Isableu, B., & Jarraya, M. (2006). Embodied spatial transformations: "body analogy" for the mental rotation of objects. *Journal of experimental psychology. General*, *135*(3), 327–347. https://doi.org/10.1037/0096-3445.135.3.327

Anderson, D. I., Campos, J. J., Witherington, D. C., Dahl, A., Rivera, M., He, M., Uchiyama, I., & Barbu-Roth, M. (2013). The role of locomotion in psychological development. *Frontiers in psychology*, *4*, 440. https://doi.org/10.3389/fpsyg.2013.00440

Antrilli, N. K., & Wang, S.-h. (2016). Visual cues generated during action facilitate 14-month-old infants' mental rotation. *Journal of Cognition and Development*, *17*(3), 418–429. https://doi.org/10.1080/15248372.2015.1058262

Baenninger, M., & Newcombe, N. (1989). The role of experience in spatial test performance: A meta-analysis. *Sex Roles*, *20*(5), 327–344. https://doi.org/10.1007/BF00287729

Bai, D. L., & Bertenthal, B. I. (1992). Locomotor status and the development of spatial search skills. *Child development*, *63*(1), 215. https://doi.org/10.2307/1130914

Baillargeon, R., Spelke, E. S., & Wasserman, S. (1985). Object permanence in five-month-old infants. *Cognition*, *20*(3), 191–208. https://doi.org/10.1016/0010-0277(85)90008-3

Baillargeon, R. (1987). Object permanence in 3½- and 4½-month-old infants. *Developmental Psychology*, *23*(5), 655–664. https://doi.org/10.1037/0012-1649.23.5.655

Bayley, N. (2005). *Psyctests dataset.* https://doi.org/10.1037/t14978-000

Beard, R., Piaget, J., & Inhelder, B. (1971). Mental imagery in the child: A study of the development of imaginal representation. *British Journal of Educational Studies*, *19*(3), 343. https://doi.org/10.2307/3120455

Beckner, A. G., Katz, M., Tompkins, D. N., Voss, A. T., Winebrake, D., LoBue, V., Oakes, L. M., & Casasola, M. (2023a). A novel approach to assessing infant and child mental rotation. *Journal of Intelligence*, *11*(8). https://doi.org/10.3390/jintelligence11080168

Beckner, A. G., Voss, A. T., Phillips, L., King, K., Casasola, M., & Oakes, L. M. (2023b). An investigation of mental rotation in infancy using change detection. *Infant behavior & development*, *71*, 101834. https://doi.org/10.1016/j.infbeh.2023.101834

Benson, J. B., & Užgiris, I. Č. (1985). Effect of self-initiated locomotion on infant search activity. *Developmental Psychology*, *21*(6), 923–931. https://doi.org/10.1037/0012-1649.21.6.923

Blender Online Community. (2017). Blender. https://www.blender.org/

Blender Online Community. (2024). Blender. https://www.blender.org/

Blüchel, M., Lehmann, J., Kellner, J., & Jansen, P. (2013). The improvement in mental rotation performance in primary school-aged children after a two-week motor-training. *Educational Psychology*, *33*(1), 75–86. https://doi.org/10.1080/01443410.2012.707612

Bogartz, R. S., Shinskey, J. L., & Schilling, T. H. (2000). Object permanence in five-and-a-half-month-old infants? *Infancy : the official journal of the International Society on Infant Studies*, *1*(4), 403–428. https://doi.org/10.1207/S15327078IN0104_3

Bourgeois, K. S., Khawar, A. W., Neal, S. A., & Lockman, J. J. (2005). Infant manual exploration of objects, surfaces, and their interrelations. *Infancy*, *8*(3), 233–252. https://doi.org/10.1207/s15327078in0803_3

Bruce, C. D., & Hawes, Z. (2015). The role of 2d and 3d mental rotation in mathematics for young children: What is it? why does it matter? and what can we do about it? *ZDM*, *47*(3), 331–343. https://doi.org/10.1007/s11858-014-0637-4

Burakevych, N., Mckinlay, C. J. D., Alsweiler, J. M., Wouldes, T. A., & Harding, J. E. (2017). Bayley-III motor scale and neurological examination at 2 years do not predict motor skills at 4.5 years. *Developmental medicine and child neurology*, *59*(2), 216–223. https://doi.org/10.1111/dmcn.13232

Caldwell, E. C., & Hall, V. C. (1970). Concept learning in discrimination tasks. *Developmental Psychology*, *2*(1), 41–48. https://doi.org/10.1037/h0028606

Campos, Anderson, Barbu-Roth, Hubbard, Hertenstein, & Witherington. (2000). Travel broadens the mind. *Infancy*, *1*(2), 149–219. https://doi.org/10.1207/S15327078IN0102_1

Campos, D., Gonçalves, V. M. G., Guerreiro, M. M., Santos, D. C., Goto, M. M. F., Arias, A. V., & Campos-Zanelli, T. M. (2012). Comparison of motor and cognitive performance in infants during the first year of life. *Pediatric physical therapy : the official publication of the Section on Pediatrics of the American Physical Therapy Association*, *24*(2), 193–7, discussion 198. https://doi.org/10.1097/PEP.0b013e31824d2db7

Campos, J. J., Anderson, D. I., & Telzrow, R. (2009). Locomotor experience influences the spatial cognitive development of infants with spina bifida. *Zeitschrift für Entwicklungspsychologie und Pädagogische Psychologie*, *41*(4), 181–188. https://doi.org/10.1026/0049-8637.41.4.181

Cannon, E. N., & Woodward, A. L. (2008). Action anticipation and interference: A test of prospective gaze. *CogSci ... Annual Conference of the Cognitive Science Society. Cognitive Science Society (U.S.). Conference*, *2008*, 981–985.

Cashon & Cohen. (2000). Eight-month-old infants' perception of possible and impossible events. *Infancy*, *1*(4), 429–446. https://doi.org/10.1207/S15327078IN0104_4

Christodoulou, J., Johnson, S. P., Moore, D. M., & Moore, D. S. (2016). Seeing double: 5-month-olds' mental rotation of dynamic, 3d block stimuli presented on dual monitors. *Infant Behavior & development*, *45*(Pt A), 64–70. https://doi.org/10.1016/j.infbeh.2016.09.005

Clearfield, M. W. (2004). The role of crawling and walking experience in infant spatial memory. *Journal of Experimental Child Psychology*, *89*(3), 214–241. https://doi.org/10.1016/j.jecp.2004.07.003

Clifton, R. K., Muir, D. W., Ashmead, D. H., & Clarkson, M. G. (1993). Is visually guided reaching in early infancy a myth? *Child development*, *64*(4), 1099–1110. https://doi.org/10.1111/j.1467-8624.1993.tb04189.x

Connolly, K. J. (1998). *The psychobiology of the hand* (Vol. no. 147). Mac Keith Press; distributed by Cambridge Univ. Press. https://psycnet.apa.org/record/2001-00487-000

Constantinescu, M., Moore, D. S., Johnson, S. P., & Hines, M. (2018). Early contributions to infants' mental rotation abilities. *Developmental science*, *21*(4), e12613. https://doi.org/10.1111/desc.12613

Cooper, L. A., & Shepard, R. N. (1973). Chronometric studies of the rotation of mental images. In *Visual information processing* (pp. 75–176). Elsevier. https://doi.org/10.1016/B978-0-12-170150-5.50009-3

Corballis, M. C., & McLaren, R. (1984). Winding one's ps and qs: Mental rotation and mirror-image discrimination. *Journal of Experimental Psychology: Human Perception and Performance*, *10*(2), 318–327. https://doi.org/10.1037//0096-1523.10.2.318

Corbetta, D., Wiener, R. F., Thurman, S. L., & McMahon, E. (2018). The embodied origins of infant reaching: Implications for the emergence of eye-hand coordination. *Kinesiology Review*, *7*(1), 10–17. https://doi.org/10.1123/kr.2017-0052

Cortes, R. A., Green, A. E., Barr, R. F., & Ryan, R. M. (2022). Fine motor skills during early childhood predict visuospatial deductive reasoning in adolescence. *Developmental Psychology*, *58*(7), 1264–1276. https://doi.org/10.1037/dev0001354

Costall, A. P. (1984). Are theories of perception necessary? a review of gibson's the ecological approach to visual perception. *Journal of the Experimental Analysis of Behavior*, *41*(1), 109–115. https://doi.org/10.1901/jeab.1984.41-109

Courbois, Y. (2000). The role of stimulus axis salience in children's ability to mentally rotate unfamiliar figures. *European Journal of Cognitive Psychology*, *12*(2), 261–269. https://doi.org/10.1080/09541446.2000.10708706

Da Resque, D. P. S., de Moura Lobato, A. M., Da Silva, C. G., Da Cruz Filho, D. A., Da Fonseca, S. S. S., de Oliveira Matos, F., & Pereira, A. (2023). The inhibition of mirror generalization of letters in school-aged children. *Frontiers in Psychology*, *14*, 996012. https://doi.org/10.3389/fpsyg.2023.996012

Dahl, A., Campos, J. J., Anderson, D. I., Uchiyama, I., Witherington, D. C., Ueno, M., Poutrain-Lejeune, L., & Barbu-Roth, M. (2013). The epigenesis of wariness of heights. *Psychological science*, *24*(7), 1361–1367. https://doi.org/10.1177/0956797613476047

Daum, M. M., Attig, M., Gunawan, R., Prinz, W., & Gredebäck, G. (2012). Actions seen through babies' eyes: A dissociation between looking time and predictive gaze. *Frontiers in Psychology*, *3*, 370. https://doi.org/10.3389/fpsyg.2012.00370

De Klerk, C. C. J. M., Southgate, V., & Csibra, G. (2016). Predictive action tracking without motor experience in 8-month-old infants. *Brain and cognition*, *109*, 131–139. https://doi.org/10.1016/j.bandc.2016.09.010

De Lisi, R., & Wolford, J. L. (2002). Improving children's mental rotation accuracy with computer game playing. *The Journal of genetic psychology*, *163*(3), 272–282. https://doi.org/10.1080/00221320209598683

Dean, A. L., & Harvey, W. O. (1979). An information-processing analysis of a piagetian imagery task. *Developmental Psychology*, *15*(4), 474–475. https://doi.org/10.1037/0012-1649.15.4.474

Del Giudice, E., Grossi, D., Angelini, R., Crisanti, A. F., Latte, F., Fragassi, N. A., & Trojano, L. (2000). Spatial cognition in children. i. development of drawing-related (visuospatial and constructional) abilities in preschool and early school years. *Brain and Development*, *22*(6), 362–367. https://doi.org/10.1016/s0387-7604(00)00158-3

Deutsch, G., Bourbon, W. T., Papanicolaou, A. C., & Eisenberg, H. M. (1988). Visuospatial tasks compared via activation of regional cerebral blood flow. *Neuropsychologia*, *26*(3), 445–452. https://doi.org/10.1016/0028-3932(88)90097-8

Dinehart, L., & Manfra, L. (2013). Associations between low-income children's fine motor skills in preschool and academic performance in second grade. *Early Education & Development*, *24*(2), 138–161. https://doi.org/10.1080/10409289.2011.636729

Ebersbach, M., & Krüger, M. (2017). Let's twist again! embodiment effects in spatial judgments on human figures rotated along a vertical axis. *Journal of Cognitive Psychology*, *29*(8), 963–976. https://doi.org/10.1080/20445911.2017.1342647

Ebert, W. M., Jost, L., & Jansen, P. (2024). Gender stereotypes in preschoolers' mental rotation. *Frontiers in psychology*, *15*, 1284314. https://doi.org/10.3389/fpsyg.2024.1284314

Ebert, W. M., Jost, L., Jansen, P., Stevanovski, B., & Voyer, D. (2025). Visual working memory as the substrate for mental rotation: A replication. *Psychonomic bulletin & review*, *32*(3), 1204–1216. https://doi.org/10.3758/s13423-024-02602-4

Ehrlich, S. B., Levine, S. C., & Goldin-Meadow, S. (2006). The importance of gesture in children's spatial reasoning. *Developmental Psychology*, *42*(6), 1259–1268. https://doi.org/10.1037/0012-1649.42.6.1259

Enge, A., Kapoor, S., Kieslinger, A.-S., & Skeide, M. A. (2023). A meta-analysis of mental rotation in the first years of life. *Developmental science*, *26*(6), e13381. https://doi.org/10.1111/desc.13381

Erdmann, K., Kavšek, M., & Heil, M. (2018). Infants' looking times in a dynamic mental rotation task: Clarifying inconsistent results. *Cognitive Development*, *48*, 279–285. https://doi.org/10.1016/j.cogdev.2018.10.002

Estes, D. (1998). Young children's awareness of their mental activity: The case of mental rotation. *Child development*, *69*(5), 1345–1360. https://doi.org/10.1111/j.1467-8624.1998.tb06216.x

Falck-Ytter, T., Gredebäck, G., & von Hofsten, C. (2006). Infants predict other people's action goals. *Nature neuroscience*, *9*(7), 878–879. https://doi.org/10.1038/nn1729

Fanari, R., Meloni, C., & Massidda, D. (2019). Visual and spatial working memory abilities predict early math skills: A longitudinal study. *Frontiers in psychology*, *10*, 2460. https://doi.org/10.3389/fpsyg.2019.02460

Fantz, R. L. (1956). A method for studying early visual development. *Perceptual and Motor Skills*, *6*(1), 13–15. https://doi.org/10.2466/pms.1956.6.g.13

Fantz, R. L. (1964). Visual experience in infants: Decreased attention to familiar patterns relative to novel ones. *Science (New York, N.Y.)*, *146*(3644), 668–670. https://doi.org/10.1126/science.146.3644.668

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior research methods*, *39*(2), 175–191. https://doi.org/10.3758/BF03193146

Fernández-Méndez, L. M., Contreras, M. J., & Elosúa, M. R. (2018). From what age is mental rotation training effective? differences in preschool age but not in sex. *Frontiers in psychology*, *9*, 753. https://doi.org/10.3389/fpsyg.2018.00753

Fernández-Méndez, L. M., Contreras, M. J., & Elosúa, M. R. (2020). Developmental differences between 1st and 3rd year of early childhood education (preschool) in mental rotation and its training. *Psychological research*, *84*(4), 1056–1064. https://doi.org/10.1007/s00426-018-1104-6

Fiske, A., Mortimer, A., Collins-Jones, L., de Klerk, C. C. J. M., Gattas, S. U., Dvergsdal, H., Scerif, G., & Holmboe, K. (2025). Inhibitory control development from infancy to early childhood: A longitudinal fnirs study. *Developmental Cognitive Neuroscience*, *73*, 101557. https://doi.org/https://doi.org/10.1016/j.dcn.2025.101557

Franchak, J. M., Kretch, K. S., Soska, K. C., & Adolph, K. E. (2011). Head-mounted eye tracking: A new method to describe infant looking. *Child development*, *82*(6), 1738–1750. https://doi.org/10.1111/j.1467-8624.2011.01670.x

Frick, A., Daum, M. M., Walser, S., & Mast, F. W. (2009). Motor processes in children's mental rotation. *Journal of Cognition and Development*, *10*(1-2), 18–40. https://doi.org/10.1080/15248370902966719

Frick, A., Ferrara, K., & Newcombe, N. S. (2013a). Using a touch screen paradigm to assess the development of mental rotation between 3½ and 5½ years of age. *Cognitive processing*, *14*(2), 117–127. https://doi.org/10.1007/s10339-012-0534-0

Frick, A., Hansen, M. A., & Newcombe, N. S. (2013b). Development of mental rotation in 3- to 5-year-old children. *Cognitive Development*, *28*(4), 386–399. https://doi.org/10.1016/j.cogdev.2013.06.002

Frick, A., & Möhring, W. (2013). Mental object rotation and motor development in 8- and 10-month-old infants. *Journal of experimental child psychology*, *115*(4), 708–720. https://doi.org/10.1016/j.jecp.2013.04.001

Frick, A., & Möhring, W. (2016). A matter of balance: Motor control is related to children's spatial and proportional reasoning skills. *Frontiers in Psychology*, *6*, 166405. https://doi.org/10.3389/fpsyg.2015.02049

Frick, A., Möhring, W., & Newcombe, N. S. (2014). Development of mental transformation abilities. *Trends in cognitive sciences*, *18*(10), 536–542. https://doi.org/10.1016/j.tics.2014.05.011

Frick, A., & Pichelmann, S. (2023). Measuring spatial abilities in children: A comparison of mental-rotation and perspective-taking tasks. *Journal of Intelligence*, *11*(8). https://doi.org/10.3390/jintelligence11080165

Frick, A., & Wang, S.-h. (2014). Mental spatial transformations in 14- and 16-month-old infants: Effects of action and observational experience. *Child development*, *85*(1), 278–293. https://doi.org/10.1111/cdev.12116

Funk, M., Brugger, P., & Wilkening, F. (2005). Motor processes in children's imagery: The case of mental rotation of hands. *Developmental science*, *8*(5), 402–408. https://doi.org/10.1111/j.1467-7687.2005.00428.x

Gallagher, J. M., & Reid, D. K. (2002). *The learning theory of piaget and inhelder*. iUniverse.

Galton, F. (1880). Visualised numerals. *Nature*, *21*(533), 252–256. https://doi.org/10.1038/021252a0

Galton, F. (1907). *Mental imagery*. https://psycnet.apa.org/record/2006-03532-016

Geer, E. A., Quinn, J. M., & Ganley, C. M. (2019). Relations between spatial skills and math performance in elementary school children: A longitudinal investigation. *Developmental Psychology*, *55*(3), 637–652. https://doi.org/10.1037/dev0000649

Gehb, G., Jovanovic, B., Kelch, A., & Schwarzer, G. (2023). The influence of active and passive motion experience on infants' visual prediction ability. *Perceptual and Motor Skills*, *130*(1), 170–190. https://doi.org/10.1177/00315125221137949

Gerhard, T. M., Culham, J. C., & Schwarzer, G. (2016). Distinct visual processing of real objects and pictures of those objects in 7- to 9-month-old infants. *Frontiers in psychology*, *7*. https://doi.org/10.3389/fpsyg.2016.00827

Gerhard, T. M., & Schwarzer, G. (2018). Impact of rotation angle on crawling and non-crawling 9-month-old infants' mental rotation ability. *Journal of experimental child psychology*, *170*, 45–56. https://doi.org/10.1016/j.jecp.2018.01.001

Gerhard-Samunda, T. M., Jovanovic, B., & Schwarzer, G. (2021). Role of manually-generated visual cues in crawling and non-crawling 9-month-old infants' mental rotation. *Cognitive Development*, *59*, 101053. https://doi.org/10.1016/j.cogdev.2021.101053

Gibson, E. J. (1970). The development of perception as an adaptive process: Perception of events in space develops early, while perception of objects shows evolution and greater dependence on learning. *American Scientist*, *58*(1), 98–107. http://www.jstor.org/stable/27828934

Gibson, E. J. (1988). Exploratory behavior in the development of perceiving, acting, and the acquiring of knowledge. *Annual Review of Psychology*, *39*(1), 1–42. https://doi.org/10.1146/annurev.ps.39.020188.000245

Gibson, E. J., & Pick, A. D. (2000). *An ecological approach to perceptual learning and development*. Oxford University Press.

Gibson, J. J. (2014). *The ecological approach to visual perception: Classic edition*. https://api.taylorfrancis.com/content/books/mono/download?identifiername=doi&identifiervalue=10.4324/9781315740218&type=googlepdf

Goel, V., & Dolan, R. J. (2003). Explaining modulation of reasoning by belief. *Cognition*, *87*(1), B11–22. https://doi.org/10.1016/s0010-0277(02)00185-3

Gold, Elicker, Kellerman, Christ, Mishra, & Howe. (2023). Engineering play, mathematics, and spatial skills in children with and without disabilities. In *Developing culturally and developmentally appropriate early stem learning experiences* (pp. 49–65). Routledge. https://doi.org/10.4324/9781032634197-4

Gottlieb, G. (1970). *Conceptions of prenatal behavior: Development and evolution of behavior: Essays in memory of t. c. schneirla*. W. H. Freeman and Company. https://opus4.kobv.de/opus4-fromm/frontdoor/index/index/docid/10913

Gottlieb, G. (1991). Experiential canalization of behavioral development: Theory. *Developmental Psychology*, *27*(1), 4–13. https://doi.org/10.1037//0012-1649.27.1.4

Gottlieb, G. (2007). Probabilistic epigenesis. *Developmental science*, *10*(1), 1–11. https://doi.org/10.1111/j.1467-7687.2007.00556.x

Gredebäck, G., & Melinder, A. (2010). Infants' understanding of everyday social interactions: A dual process account. *Cognition*, *114*(2), 197–206. https://doi.org/10.1016/j.cognition.2009.09.004

Gredebäck, G., & von Hofsten, C. (2004). Infants' evolving representations of object motion during occlusion: A longitudinal study of 6- to 12-month-old infants. *Infancy : the official journal of the International Society on Infant Studies*, *6*(2), 165–184. https://doi.org/10.1207/s15327078in0602_2

Hahn, N., Jansen, P., & Heil, M. (2010). Preschoolers' mental rotation of letters: Sex differences in hemispheric asymmetry. *Cognitive neuroscience*, *1*(4), 261–267. https://doi.org/10.1080/17588928.2010.485248

Haith, M. M. (1998). Who put the cog in infant cognition? is rich interpretation too costly? *Infant Behavior and Development*, *21*(2), 167–179. https://doi.org/10.1016/s0163-6383(98)90001-7

Hawes, Z., LeFevre, J.-.-A., Xu, C., & Bruce, C. D. (2015a). Mental rotation with tangible three–dimensional objects: A new measure sensitive to developmental differences in 4– to 8–year–old children. *Mind, Brain, and Education*, *9*(1), 10–18. https://doi.org/10.1111/mbe.12051

Hawes, Z., Moss, J., Caswell, B., & Poliszczuk, D. (2015b). Effects of mental rotation training on children's spatial and mathematics performance: A randomized controlled study. *Trends in Neuroscience and Education*, *4*(3), 60–68. https://doi.org/10.1016/j.tine.2015.05.001

Hegarty, M. (2004). Mechanical reasoning by mental simulation. *Trends in cognitive sciences*, *8*(6), 280–285. https://doi.org/10.1016/j.tics.2004.04.001

Heil, M., & Rolke, B. (2002). Toward a chronopsychophysiology of mental rotation. *Psychophysiology*, *39*(4), 414–422.

Hespos, S. J., & Rochat, P. (1997). Dynamic mental representation in infancy. *Cognition*, *64*(2), 153–188. https://doi.org/10.1016/S0010-0277(97)00029-2

Hospodar, C. M., & Adolph, K. E. (2024). The development of gait and mobility: Form and function in infant locomotion. *Wiley Interdisciplinary Reviews: Cognitive Science*, *15*(4), e1677. https://doi.org/10.1002/wcs.1677

Hoyek, N., Collet, C., Fargier, P., & Guillot, A. (2012). The use of the vandenberg and kuse mental rotation test in children. *Journal of Individual Differences*, *33*(1), 62–67. https://doi.org/10.1027/1614-0001/a000063

Iachini, T., Ruggiero, G., Bartolo, A., Rapuano, M., & Ruotolo, F. (2019). The effect of body-related stimuli on mental rotation in children, young and elderly adults. *Scientific reports*, *9*(1), 1169. https://doi.org/10.1038/s41598-018-37729-7

Jahoda, G. (1979). On the nature of difficulties in spatial-perceptual tasks: Ethnic and sex differences. *British journal of psychology (London, England : 1953)*, *70*(3), 351–363. https://doi.org/10.1111/j.2044-8295.1979.tb01705.x

James, W. (1890). *The principles of psychology, vol i*. Henry Holt and Co. https://doi.org/10.1037/10538-000

Jäncke, L., Kleinschmidt, A., Mirzazade, S., Shah, N. J., & Freund, H. J. (2001). The role of the inferior parietal cortex in linking the tactile perception and manual construction of object shapes. *Cerebral cortex (New York, N.Y. : 1991)*, *11*(2), 114–121. https://doi.org/10.1093/cercor/11.2.114

Jansen, P., Schmelter, A., Quaiser-Pohl, C., Neuburger, S., & Heil, M. (2013). Mental rotation performance in primary school age children: Are there gender differences in chronometric tests? *Cognitive Development*, *28*(1), 51–62. https://doi.org/10.1016/j.cogdev.2012.08.005

Jansen, P., & Heil, M. (2010). The relation between motor development and mental rotation ability in 5- to 6-year-old children. *International Journal of Developmental Science*, *4*(1), 67–75. https://doi.org/10.3233/DEV-2010-4105

Jansen, P., Lange, L., & Heil, M. (2011a). The influence of juggling on mental rotation performance in children. *Biomedical Human Kinetics*, *3*(2011), 18–22. https://doi.org/10.2478/v10101-011-0005-6

Jansen, P., Quaiser-Pohl, C., Neuburger, S., & Ruthsatz, V. (2015). Factors influencing mental-rotation with action-based gender-stereotyped objects—the role of fine motor skills. *Current Psychology*, *34*(2), 466–476. https://doi.org/10.1007/s12144-014-9269-7

Jansen, P., Schmelter, A., Kasten, L., & Heil, M. (2011b). Impaired mental rotation performance in overweight children. *Appetite*, *56*(3), 766–769. https://doi.org/10.1016/j.appet.2011.02.021

Jaščenoka, J., & Petermann, F. (2018). Leistungsinventar zur objektiven überprüfung der motorik von 3- bis 6-jährigen (lomo 3 – 6). *Frühe Bildung*, *7*(4), 241–243. https://doi.org/10.1026/2191-9186/a000398

JASP Team. (2024). Jasp. https://jasp-stats.org/

Jenni, O. G., Chaouch, A., Caflisch, J., & Rousson, V. (2013). Infant motor milestones: Poor predictive value for outcome of healthy children. *Acta paediatrica (Oslo, Norway : 1992)*, *102*(4), e181–4. https://doi.org/10.1111/apa.12129

Johnson, S. P., Gavin Bremner, J., Slater, A. M., Shuwairi, S. M., Mason, U., Spring, J., & Usherwood, B. (2012). Young infants' perception of the trajectories of two- and three-dimensional objects. *Journal of experimental child psychology*, *113*(1), 177–185. https://doi.org/10.1016/j.jecp.2012.04.011

Johnson, S. P., & Moore, D. S. (2020). Spatial thinking in infancy: Origins and development of mental rotation between 3 and 10 months of age. *Cognitive research: principles and implications*, *5*(1), 10. https://doi.org/10.1186/s41235-020-00212-x

Jolicœur, P., Regehr, S., Smith, L. B. J. P., & Smith, G. N. (1985). Mental rotation of representations of two-dimensional and three-dimensional objects. *Canadian Journal of Psychology / Revue canadienne de psychologie*, *39*(1), 100–129. https://doi.org/10.1037/h0080118

Jovanovic, B., Duemmler, T., & Schwarzer, G. (2008). Infant development of configural object processing in visual and visual-haptic contexts. *Acta Psychologica*, *129*(3), 376–386. https://doi.org/10.1016/j.actpsy.2008.09.003

Just, M. A., & Carpenter, P. A. (1985). Cognitive coordinate systems: Accounts of mental rotation and individual differences in spatial ability. *Psychological Review*, *92*(2), 137–172. https://doi.org/10.1037/0033-295x.92.2.137

Kaaz, T., & Heil, M. (2020). Infants' looking times in a 2–d mental rotation task. *Infant and Child Development*, *29*(2). https://doi.org/10.1002/icd.2167

Kaess, D. W. (1971). Measures of form constancy: Developmental trends. *Developmental Psychology*, *4*(2), 296. https://doi.org/10.1037/h0030443

Kaess, D. W., Haynes, S. D., Craig, M. J., Pearson, S. C., & Greenwell, J. (1974). Effect of distance and size of standard object on the development of shape constancy. *Journal of Experimental Psychology*, *102*(1), 17–21. https://doi.org/10.1037/h0035715

Kail, R. (1991). Controlled and automatic processing during mental rotation. *Journal of Experimental Child Psychology*, *51*(3), 337–347. https://doi.org/10.1016/0022-0965(91)90081-3

Kail, R., Pellegrino, J., & Carter, P. (1980). Developmental changes in mental rotation. *Journal of experimental child psychology*, *29*(1), 102–116. https://doi.org/10.1016/0022-0965(80)90094-6

Kaltner, S., & Jansen, P. (2017). Erratum: Developmental changes in mental rotation: A dissociation between object-based and egocentric transformations. *Advances in cognitive psychology*, *13*(2), 188–189. https://doi.org/10.5709/acp-0218-6

Karl, J. M., Sacrey, L.-A. R., & Whishaw, I. Q. (2018a). Multiple motor channel theory and the development of skilled hand movements in human infants. In D. Corbetta & M. Santello (Eds.), *Reach-to-grasp behavior: Brain, behavior, and modelling across the life span* (pp. 42–68). Routledge. https://doi.org/10.4324/9780429467875-3

Karl, J. M., Slack, B. M., Wilson, A. M., Wilson, C. A., & Bertoli, M. E. (2019). Increasing task precision demands reveals that the reach and grasp remain subject to different perception-action constraints in 12-month-old human infants. *Infant behavior & development*, *57*, 101382. https://doi.org/10.1016/j.infbeh.2019.101382

Karl, J. M., Wilson, A. M., Bertoli, M. E., & Shubear, N. S. (2018b). Touch the table before the target: Contact with an underlying surface may assist the development of precise visually controlled reach and grasp movements in human infants. *Experimental Brain Research*, *236*(8), 2185–2207. https://doi.org/10.1007/s00221-018-5293-4

Kaufmann, L., Landerl, M., Nazzoldi, M., Moeller, K., Pastore, N., & Salandin, M. (2008). Neuropsychologisches screening für 5–11-jährige — BVN/NPS 5–11.

Kelch, A., Schwarzer, G., Gehb, G., & Jovanovic, B. (2021). How 9-month-old crawling infants profit from visual-manual rotations in a mental rotation task. *Infant behavior & development*, *65*, 101642. https://doi.org/10.1016/j.infbeh.2021.101642

Kell, H. J., Lubinski, D., Benbow, C. P., & Steiger, J. H. (2013). Creativity and technical innovation: Spatial ability's unique role. *Psychological science*, *24*(9), 1831–1836. https://doi.org/10.1177/0956797613478615

Kermoian, R., & Campos, J. J. (1988). Locomotor experience: A facilitator of spatial cognitive development. *Child development*, *59*(4), 908. https://doi.org/10.2307/1130258

Knauff, M. (2007). How our brains reason logically. *Topoi*, *26*(1), 19–36. https://doi.org/10.1007/s11245-006-9002-8

Kontra, C., Goldin-Meadow, S., & Beilock, S. L. (2012). Embodied learning across the life span. *Topics in cognitive science*, *4*(4), 731–739. https://doi.org/10.1111/j.1756-8765.2012.01221.x

Kosslyn, S. M., Behrmann, M., & Jeannerod, M. (1995). The cognitive neuroscience of mental imagery. *Neuropsychologia*, *33*(11), 1335–1344. https://doi.org/10.1016/0028-3932(95)00067-d

Kosslyn, S. M., Ganis, G., & Thompson, W. L. (2001). Neural foundations of imagery. *Nature reviews. Neuroscience*, *2*(9), 635–642. https://doi.org/10.1038/35090055

Kosslyn, S. M., Ball, T. M., & Reiser, B. J. (1978). Visual images preserve metric spatial information: Evidence from studies of image scanning. *Journal of Experimental Psychology: Human Perception and Performance*, *4*(1), 47–60. https://doi.org/10.1037//0096-1523.4.1.47

Kosslyn, S. M., Margolis, J. A., Barrett, A. M., Goldknopf, E. J., & Daly, P. F. (1990). Age differences in imagery abilities. *Child development*, *61*(4), 995–1010. https://doi.org/10.1111/j.1467-8624.1990.tb02837.x

Kosslyn, S. M., Thompson, W. L., & Ganis, G. (2006). *The case for mental imagery*. Oxford University Press.

Kosslyn, S. M. (1980). *Image and mind*. Harvard University Press.

Krüger, M., Amorim, M.-A., & Ebersbach, M. (2014a). Mental rotation and the motor system: Embodiment head over heels. *Acta Psychologica*, *145*, 104–110. https://doi.org/10.1016/j.actpsy.2013.11.004

Krüger, M., & Ebersbach, M. (2018). Mental rotation and the human body: Children's inflexible use of embodiment mirrors that of adults. *The British journal of developmental psychology*, *36*(3), 418–437. https://doi.org/10.1111/bjdp.12228

Krüger, M., Kaiser, M., Mahler, K., Bartels, W., & Krist, H. (2014b). Analogue mental transformations in 3-year-olds: Introducing a new mental rotation paradigm suitable for young children. *Infant and Child Development*, *23*(2), 123–138. https://doi.org/10.1002/icd.1815

Krüger, M., & Krist, H. (2009). Imagery and motor processes — when are they connected? the mental rotation of body parts in development. *Journal of Cognition and Development*, *10*(4), 239–261. https://doi.org/10.1080/15248370903389341

Kubicek, C., Jovanovic, B., & Schwarzer, G. (2017a). How manual object exploration is associated with 7– to 8–month–old infants' visual prediction abilities in spatial object processing. *Infancy*, *22*(6), 857–873. https://doi.org/10.1111/infa.12195

Kubicek, C., Jovanovic, B., & Schwarzer, G. (2017b). The relation between crawling and 9-month-old infants' visual prediction abilities in spatial object processing. *Journal of experimental child psychology*, *158*, 64–76. https://doi.org/10.1016/j.jecp.2016.12.009

Kubicek, C., & Schwarzer, G. (2018). On the relation between infants' spatial object processing and their motor skills. *Journal of Motor Learning and Development*, *6*(s1), S6–S23. https://doi.org/10.1123/jmld.2016-0062

Kucian, K., von Aster, M., Loenneker, T., Dietrich, T., Mast, F. W., & Martin, E. (2007). Brain activation during mental rotation in school children and adults. *Journal of neural transmission (Vienna, Austria : 1996)*, *114*(5), 675–686. https://doi.org/10.1007/s00702-006-0604-5

Kung, K. T. F., & Hines, M. (2025). A 10-year longitudinal relationship between preschool sex-typical play behavior at age 3.5 years and mental rotation performance in adolescence at age 13 years. *Archives of sexual behavior*, *54*(6), 2057–2068. https://doi.org/10.1007/s10508-025-03188-1

Kunin, L., Piccolo, S. H., Saxe, R., & Liu, S. (2024). Perceptual and conceptual novelty independently guide infant looking behaviour: A systematic review and meta-analysis. *Nature human behaviour*, *8*(12), 2342–2356. https://doi.org/10.1038/s41562-024-01965-x

Lambrey, S., Doeller, C., Berthoz, A., & Burgess, N. (2012). Imagining being somewhere else: Neural basis of changing perspective in space. *Cerebral cortex (New York, N.Y. : 1991)*, *22*(1), 166–174. https://doi.org/10.1093/cercor/bhr101

Lauer, J. E., & Lourenco, S. F. (2016). Spatial processing in infancy predicts both spatial and mathematical aptitude in childhood. *Psychological science*, *27*(10), 1291–1298. https://doi.org/10.1177/0956797616655977

Lauer, J. E., Udelson, H. B., Jeon, S. O., & Lourenco, S. F. (2015). An early sex difference in the relation between mental rotation and object preference. *Frontiers in psychology*, *6*, 558. https://doi.org/10.3389/fpsyg.2015.00558

Lauer, J. E., Yhang, E., & Lourenco, S. F. (2019). The development of gender differences in spatial reasoning: A meta-analytic review. *Psychological Bulletin*, *145*(6), 537–565. https://doi.org/10.1037/bul0000191

Lehmann, J., Quaiser-Pohl, C., & Jansen, P. (2014). Correlation of motor skill, mental rotation, and working memory in 3- to 6-year-old children. *European Journal of Developmental Psychology*, *11*(5), 560–573. https://doi.org/10.1080/17405629.2014.888995

Levine, S. C., Huttenlocher, J., Taylor, A., & Langrock, A. (1999). Early sex differences in spatial skill. *Developmental Psychology*, *35*(4), 940–949. https://doi.org/10.1037/0012-1649.35.4.940

Levine, S. C., Foley, A., Lourenco, S., Ehrlich, S., & Ratliff, K. (2016). Sex differences in spatial cognition: Advancing the conversation. *Wiley Interdisciplinary Reviews: Cognitive Science*, *7*(2), 127–155. https://doi.org/10.1002/wcs.1380

Levine, S. C., Ratliff, K. R., Huttenlocher, J., & Cannon, J. (2012). Early puzzle play: A predictor of preschoolers' spatial transformation skill. *Developmental Psychology*, *48*(2), 530–542. https://doi.org/10.1037/a0025913

Li, H., Forbes, A., & Yang, W. (2021). Developing culturally and developmentally appropriate early stem learning experiences. *Early Education & Development*, *32*(1), 1–6. https://doi.org/10.1080/10409289.2020.1833674

Libertus, K., & Needham, A. (2010). Teach to reach: The effects of active vs. passive reaching experiences on action and perception. *Vision research*, *50*(24), 2750–2757. https://doi.org/10.1016/j.visres.2010.09.001

Linn, M. C., & Petersen, A. C. (1985). Emergence and characterization of sex differences in spatial ability: A meta-analysis. *Child development*, *56*(6), 1479. https://doi.org/10.2307/1130467

Lockman, J. J. (1990). *Perceptuomotor coordination in infancy*. https://doi.org/10.1016/s0166-4115(08)60096-5

Marmor, G. S. (1977). Mental rotation and number conservation: Are they related? *Developmental Psychology*, *13*(4), 320–325. https://doi.org/10.1037/0012-1649.13.4.320

Marmor, G. S. (1975). Development of kinetic images: When does the child first represent movement in mental images? *Cognitive Psychology*, *7*(4), 548–559. https://doi.org/10.1016/0010-0285(75)90022-5

Mash, C., Arterberry, M. E., & Bornstein, M. H. (2007). Mechanisms of visual object recognition in infancy: Five-month-olds generalize beyond the interpolation of familiar views. *Infancy*, *12*(1), 31–43. https://doi.org/10.1111/j.1532-7078.2007.tb00232.x

Michalec, D. (2011). Bayley scales of infant development: Third edition. In S. Goldstein & J. A. Naglieri (Eds.), *Encyclopedia of child behavior and development* (p. 215). Springer US. https://doi.org/10.1007/978-0-387-79061-9_295

Miura, S., Oshikiri, T., Miura, Y., Takiguchi, G., Takase, N., Hasegawa, H., Yamamoto, M., Kanaji, S., Matsuda, Y., Yamashita, K., Matsuda, T., Nakamura, T., Suzuki, S., & Kakeji, Y. (2019). Optimal monitor positioning and camera rotation angle for mirror image: Overcoming reverse alignment during laparoscopic colorectal surgery. *Scientific reports*, *9*(1), 8371. https://doi.org/10.1038/s41598-019-44939-0

Mix, K. S., Levine, S. C., Cheng, Y.-L., Stockton, J. D., & Bower, C. (2021). Effects of spatial training on mathematics in first and sixth grade children. *Journal of Educational Psychology*, *113*(2), 304–314. https://doi.org/10.1037/edu0000494

Möhring, W., & Frick, A. (2013). Touching up mental rotation: Effects of manual experience on 6-month-old infants' mental object rotation. *Child development*, *84*(5), 1554–1565. https://doi.org/10.1111/cdev.12065

Moore, D. S., & Cocas, L. A. (2006). Perception precedes computation: Can familiarity preferences explain apparent calculation by human babies? *Developmental Psychology*, *42*(4), 666–678. https://doi.org/10.1037/0012-1649.42.4.666

Moore, D. S., & Johnson, S. P. (2008). Mental rotation in human infants: A sex difference. *Psychological science*, *19*(11), 1063–1066. https://doi.org/10.1111/j.1467-9280.2008.02200.x

Moore, D. S., & Johnson, S. P. (2011). Mental rotation of dynamic, three-dimensional stimuli by 3-month-old infants. *Infancy*, *16*(4), 435–445. https://doi.org/10.1111/j.1532-7078.2010.00058.x

Moore, D. S., Moore, D. M., & Johnson, S. P. (2024). Minding the gap: A sex difference in young infants' mental rotation through thirty degrees of arc. *Frontiers in Psychology*, *Volume 15 - 2024*. https://doi.org/10.3389/fpsyg.2024.1415651

Morales, J, González, M, L., Guerra, M, Virgili, C, Unnithan, & V. (2011). Physical activity, perceptual-motor performance, and academic learning in 9-to-16-years-old school children. *International Journal of Sport Psychology*, *42*(4), 401–415. https://psycnet.apa.org/record/2011-19374-005

Morawietz, C., Wissmann, A. M., & Muehlbauer, T. (2024). A 6-week coordinative motor training program improves spatial ability performances in healthy children. *Frontiers in Cognition*, *3*. https://doi.org/10.3389/fcogn.2024.1396399

Münzer, S. (2015). Facilitating recognition of spatial structures through animation and the role of mental rotation ability. *Learning and Individual Differences*, *38*, 76–82. https://doi.org/10.1016/j.lindif.2014.12.007

Nagai, Y. (2019). Predictive learning: Its key role in early cognitive development. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, *374*(1771), 20180030. https://doi.org/10.1098/rstb.2018.0030

Needham, A. (2000). Improvements in object exploration skills may facilitate the development of object segregation in early infancy. *Journal of Cognition and Development*, *1*(2), 131–156. https://doi.org/10.1207/S15327647JCD010201

Needham, A., & Libertus, K. (2011). Embodiment in early development. *Wiley interdisciplinary reviews. Cognitive science*, *2*(1), 117–123. https://doi.org/10.1002/wcs.109

Newcombe & Huttenlocher. (2000). *Making space: The development of spatial representation and reasoning*. MIT Press.

Newcombe, N. S. (2018). Three kinds of spatial cognition. In *Stevens' handbook of experimental psychology and cognitive neuroscience* (pp. 1–31). John Wiley & Sons, Ltd. https://doi.org/https://doi.org/10.1002/9781119170174.epcn315

Newcombe, N. S., & Frick, A. (2010). Early education for spatial intelligence: Why, what, and how. *Mind, Brain, and Education*, *4*(3), 102–111. https://doi.org/10.1111/j.1751-228X.2010.01089.x

Newcombe, N. S., Uttal, D. H., & Sauter, M. (2013). *Spatial development.* Oxford University Press. https://doi.org/10.1093/oxfordhb/9780199958450.013.0020

Oakes, L. M. (2010). Using habituation of looking time to assess mental processes in infancy. *Journal of Cognition and Development*, *11*(3), 255–268. https://doi.org/10.1080/15248371003699977

Oakes, L. M., Sperka, D., DeBolt, M. C., & Cantrell, L. M. (2019). Habit2: A stand-alone software solution for presenting stimuli and recording infant looking times in order to study infant development. *Behavior research methods*, *51*(5), 1943–1952. https://doi.org/10.3758/s13428-019-01244-y

Örnkloo, H., & von Hofsten, C. (2007). Fitting objects into holes: On the development of spatial cognition skills. *Developmental Psychology*, *43*(2), 404–416. https://doi.org/10.1037/0012-1649.43.2.404

Oudgenoeg-Paz, O., Leseman, P. P. M., & Volman, M. J. M. (2015). Exploration as a mediator of the relation between the attainment of motor milestones and the development of spatial cognition and spatial language. *Developmental Psychology*, *51*(9), 1241–1253. https://doi.org/10.1037/a0039572

Parsons, L. M. (1987). Imagined spatial transformations of one's hands and feet. *Cognitive Psychology*, *19*(2), 178–241. https://doi.org/10.1016/0010-0285(87)90011-9

Parsons, L. M. (1994). Temporal and kinematic properties of motor behavior reflected in mentally simulated action. *Journal of Experimental Psychology: Human Perception and Performance*, *20*(4), 709–730. https://doi.org/10.1037/0096-1523.20.4.709

Paulus, M. (2011). How infants relate looker and object: Evidence for a perceptual learning account of gaze following in infancy. *Developmental science*, *14*(6), 1301–1310. https://doi.org/10.1111/j.1467-7687.2011.01076.x

Paulus, M., Hunnius, S., & Bekkering, H. (2011). Can 14- to 20-month-old children learn that a tool serves multiple purposes? a developmental study on children's action goal prediction. *Vision research*, *51*(8), 955–960. https://doi.org/10.1016/j.visres.2010.12.012

Pearson, J. (2019). The human imagination: The cognitive neuroscience of visual mental imagery. *Nature reviews. Neuroscience*, *20*(10), 624–634. https://doi.org/10.1038/s41583-019-0202-9

Pearson, J., Naselaris, T., Holmes, E. A., & Kosslyn, S. M. (2015). Mental imagery: Functional mechanisms and clinical applications. *Trends in cognitive sciences*, *19*(10), 590–602. https://doi.org/10.1016/j.tics.2015.08.003

Pedrett, S., Chavaillaz, A., & Frick, A. (2023). Age-related changes in how 3.5- to 5.5-year-olds observe and imagine rotational object motion. *Spatial Cognition & Computation*, *23*(2), 83–111. https://doi.org/10.1080/13875868.2022.2095276

Pedrett, S., Kaspar, L., & Frick, A. (2020). Understanding of object rotation between two and three years of age. *Developmental Psychology*, *56*(2), 261–274. https://doi.org/10.1037/dev0000871

Piaget. (1952). The origins of intelligence in children. *International University.*

Piaget, J., & Cook, M. (1954). *The construction of reality in the child.* Basic Books. https://doi.org/10.1037/11168-000

Piek, J. P., Dawson, L., Smith, L. M., & Gasson, N. (2008). The role of early fine and gross motor development on later motor and cognitive ability. *Human movement science*, *27*(5), 668–681. https://doi.org/10.1016/j.humov.2007.11.002

Pinquart, M., Schwarzer, G., & Zimmermann, P. (2018). *Entwicklungspsychologie - kindes- und jugendalter.* Hogrefe Verlag GmbH & Co. KG. https://doi.org/10.1026/02861-000

Piri, Z., & Cagiltay, K. (2024). Can 3-dimensional visualization enhance mental rotation (mr) ability?: A systematic review. *International Journal of Human–Computer Interaction*, *40*(14), 3683–3698. https://doi.org/10.1080/10447318.2023.2196161

Platt, J. E., & Cohen, S. (1981). Mental rotation task performance as a function of age and training. *The Journal of Psychology*, *108*(2), 173–178. https://doi.org/10.1080/00223980.1981.9915260

Poucet, B. (1993). Spatial cognitive maps in animals: New hypotheses on their structure and neural mechanisms. *Psychological Review*, *100*(2), 163–182. https://doi.org/10.1037//0033-295x.100.2.163

Preißler, L., Jovanovic, B., Munzert, J., Schmidt, F., Fleming, R. W., & Schwarzer, G. (2021). Effects of visual and visual-haptic perception of material rigidity on reaching and grasping in the course of development. *Acta Psychologica*, *221*, 103457. https://doi.org/10.1016/j.actpsy.2021.103457

Prinz, W. (1990). A common coding approach to perception and action. In O. Neumann & W. Prinz (Eds.), *Relationships between perception and action* (pp. 167–201). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-75348-0_

Puranik, C. S., & Lonigan, C. J. (2012). Name-writing proficiency, not length of name, is associated with preschool children's emergent literacy skills. *Early Childhood Research Quarterly*, *27*(2), 284–294. https://doi.org/10.1016/j.ecresq.2011.09.003

Quaiser-Pohl, C. (2003). The mental cutting test "schnitte" and the picture rotation test-two new measures to assess spatial ability. *International Journal of Testing*, *3*(3), 219–231. https://doi.org/10.1207/S15327574IJT0303_2

Quaiser-Pohl, C., Rohe, A. M., & Amberger, T. (2010). The solution strategy as an indicator of the developmental stage of preschool children's mental-rotation ability. *Journal of Individual Differences*, *31*(2), 95–100. https://doi.org/10.1027/1614-0001/a000017

Quinn, P. C., & Liben, L. S. (2008). A sex difference in mental rotation in young infants. *Psychological science*, *19*(11), 1067–1070. https://doi.org/10.1111/j.1467-9280.2008.02201.x

Quinn, P. C., & Liben, L. S. (2014). A sex difference in mental rotation in infants: Convergent evidence. *Infancy*, *19*(1), 103–116. https://doi.org/10.1111/infa.12033

Raven, J. (2003). Raven progressive matrices. *Handbook of nonverbal assessment*, 223–237.

Raven, J. C., Raven, J., & & Court, J. H. (2002). *Raven's progressive matrices und vocabulary scales. coloured progressive matrices mit der parallelform des tests und der puzzle-form*. https://www.fachportal-hochbegabung.de/intelligenz-tests/cpm-coloured-progressive-matrices/

Ravid-Roth, T., Kunde, W., Jaffe-Dax, S., & Eitam, B. (2025). Learning to move, moving to learn: A quarter century of insights into infant motor development. *Infant behavior & development*, *81*, 102131. https://doi.org/10.1016/j.infbeh.2025.102131

Reuner, Gitta, Rosenkranz, & Joachim. (2014). *Bayley scales of infant and toddler development – third edition (bayley-iii), deutsche fassung*. Pearson. https://www.pearsonclinical.de/bayley-iii.html

Rimfeld, K., Shakeshaft, N. G., Malanchini, M., Rodic, M., Selzam, S., Schofield, K., Dale, P. S., Kovas, Y., & Plomin, R. (2017). Phenotypic and genetic evidence for a unifactorial structure of spatial abilities. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(10), 2777–2782. https://doi.org/10.1073/pnas.1607883114

Rochat, P., & Hespos, S. J. (1996). Tracking and anticipation of invisible spatial transformations by 4- to 8-month-old infants. *Cognitive Development*, *11*(1), 3–17. https://doi.org/10.1016/S0885-2014(96)90025-8

Rodriguez, K. A., Ralph, Y. K., de la Rosa, I. M., Corro, O. P. P., Ochoa, C. D. R., & Pruden, S. M. (2025). Leveraging eye-tracking technology to understand how young children solve a mental rotation task [e70018 ICD-24-0193.R2]. *Infant and Child Development*, *34*(3), e70018. https://doi.org/https://doi.org/10.1002/icd.70018

Ross-Sheehy, S., Oakes, L. M., & Luck, S. J. (2003). The development of visual short-term memory capacity in infants. *Child development*, *74*(6), 1807–1822. https://doi.org/10.1046/j.1467-8624.2003.00639.x

Rüsseler, J., Scholz, J., Jordan, K., & Quaiser-Pohl, C. (2005). Mental rotation of letters, pictures, and three-dimensional objects in german dyslexic children. *Child neuropsychology : a journal on normal and abnormal development in childhood and adolescence*, *11*(6), 497–512. https://doi.org/10.1080/09297040490920168

Sack, A. T., Lindner, M., & Linden, D. E. J. (2007). Object- and direction-specific interference between manual and mental rotation. *Perception & psychophysics*, *69*(8), 1435–1449. https://doi.org/10.3758/BF03192958

Schmidtke, A., & Schaller, S. (1980). Comparative study of factor structure of raven's coloured progressive matrices. *Perceptual and Motor Skills*, *51*(3 Pt 2), 1244–1246. https://doi.org/10.2466/pms.1980.51.3f.1244

Schneider, J. L. (2025). Environments "develop": Infant motor development can inform the study of physical space. *New Ideas in Psychology*, *76*, 101125. https://doi.org/10.1016/j.newideapsych.2024.101125

Schwarzer, G. (2014). How motor and visual experiences shape infants' visual processing of objects and faces. *Child Development Perspectives*, *8*(4), 213–217. https://doi.org/10.1111/cdep.12093

Schwarzer, G., Freitag, C., Buckel, R., & Lofruthe, A. (2013a). Crawling is associated with mental rotation ability by 9–month–old infants. *Infancy*, *18*(3), 432–441. https://doi.org/10.1111/j.1532-7078.2012.00132.x

Schwarzer, G., Freitag, C., & Schum, N. (2013b). How crawling and manual object exploration are related to the mental rotation abilities of 9-month-old infants. *Frontiers in psychology*, *4*, 97. https://doi.org/10.3389/fpsyg.2013.00097

Schwarzer, G., Gehb, G., Kelch, A., Gerhard-Samunda, T., & Jovanovic, B. (2022). Locomotion training contributes to 6-month-old infants' mental rotation ability. *Human movement science*, *85*, 102979. https://doi.org/10.1016/j.humov.2022.102979

Schwarzer, G., & Jovanovic, B. (2015). *Entwicklungspsychologie der kindheit* (1. Auflage). Verlag W. Kohlhammer.

Schwarzer, G., & Jovanovic, B. (2024). Infants' predictive minds: The role of motor experience. *Child Development Perspectives*, *18*(3), 123–128. https://doi.org/10.1111/cdep.12506

Scott, K., Chu, J., & Schulz, L. (2017). Lookit (part 2): Assessing the viability of online developmental research, results from three case studies. *Open Mind*, *1*(1), 15–29. https://doi.org/10.1162/OPMI_a_00001

Sekiyama, K., Kinoshita, T., & Soshi, T. (2014). Strong biomechanical constraints on young children's mental imagery of hands. *Royal Society open science*, *1*(4), 140118. https://doi.org/10.1098/rsos.140118

Serino, G., & Ossmy, O. (2025). Toward a causal science of early play? *Infancy*, *30*(4), e70033. https://doi.org/10.1111/infa.70033

Shepard & Metzler. (1971). Mental rotation of three-dimensional objects. *Science (New York, N.Y.)*, *171*(3972), 701–703. https://doi.org/10.1126/science.171.3972.701

Shepard, S., & Metzler, D. (1988). Mental rotation: Effects of dimensionality of objects and type of task. *Journal of Experimental Psychology: Human Perception and Performance*, *14*(1), 3–11. https://doi.org/10.1037/0096-1523.14.1.3

Slone, L. K., Moore, D. S., & Johnson, S. P. (2018). Object exploration facilitates 4-month-olds' mental rotation performance. *PloS one*, *13*(8), e0200468. https://doi.org/10.1371/journal.pone.0200468

Soska, K. C., Adolph, K. E., & Johnson, S. P. (2010). Systems in development: Motor skill acquisition facilitates three-dimensional object completion. *Developmental Psychology*, *46*(1), 129–138. https://doi.org/10.1037/a0014618

Soska, K. C., & Johnson, S. P. (2013). Development of three-dimensional completion of complex objects. *Infancy*, *18*(3), 325–344. https://doi.org/10.1111/j.1532-7078.2012.00127.x

Spelke, E. S. (1998). Nativism, empiricism, and the origins of knowledge. *Infant Behavior and Development*, *21*(2), 181–200. https://doi.org/10.1016/S0163-6383(98)90002-9

Spelke, E. S., & von Hofsten, C. (2001). Predictive reaching for occluded objects by 6-month-old infants. *Journal of Cognition and Development*, *2*(3), 261–281. https://doi.org/10.1207/s15327647jcd0203_2

Spitz, R. A. (1958). On the genesis of superego components. *The Psychoanalytic study of the child*, *13*, 375–404. https://doi.org/10.1080/00797308.1958.11823188

Stark, P., Bozkir, E., Sójka, W., Huff, M., Kasneci, E., & Göllner, R. (2024). The impact of presentation modes on mental rotation processing: A comparative analysis of eye movements and performance. *Scientific reports*, *14*(1), 12329. https://doi.org/10.1038/s41598-024-60370-6

Stieff, M. (2007). Mental rotation and diagrammatic reasoning in science. *Learning and Instruction*, *17*(2), 219–234. https://doi.org/10.1016/j.learninstruc.2007.01.012

Striano, T., & Bushnell, E. W. (2005). Haptic perception of material properties by 3-month-old infants. *Infant Behavior and Development*, *28*(3), 266–289. https://doi.org/10.1016/j.infbeh.2005.05.008

Terlecki, M. S., & Newcombe, N. S. (2005). How important is the digital divide? the relation of computer and videogame usage to gender differences in mental rotation ability. *Sex Roles*, *53*(5-6), 433–441. https://doi.org/10.1007/s11199-005-6765-0

Thelen, E. (2005). Dynamic systems theory and the complexity of change. *Psychoanalytic Dialogues*, *15*(2), 255–283. https://doi.org/10.1080/10481881509348831

Thelen, E., & Smith, L. B. (1994). *A dynamic systems approach to the development of cognition and action*. MIT Press.

Titze, C., Jansen, P., & Heil, M. (2010). Mental rotation performance and the effect of gender in fourth graders and adults. *European Journal of Developmental Psychology*, *7*(4), 432–444. https://doi.org/10.1080/17405620802548214

Tobii Pro. (2022). Tobii pro lab. https://www.tobii.com/

Uchiyama, I., Anderson, D. I., Campos, J. J., Witherington, D., Frankel, C. B., Lejeune, L., & Barbu-Roth, M. (2008). Locomotor experience affects self and emotion. *Developmental Psychology*, *44*(5), 1225–1231. https://doi.org/10.1037/a0013224

Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A. R., Warren, C., & Newcombe, N. S. (2013). The malleability of spatial skills: A meta-analysis of training studies. *Psychological Bulletin*, *139*(2), 352–402. https://doi.org/10.1037/a0028446

van der Fels, I. M. J., Te Wierike, S. C. M., Hartman, E., Elferink-Gemser, M. T., Smith, J., & Visscher, C. (2015). The relationship between motor skills and cognitive skills in 4-16 year old typically developing children: A systematic review. *Journal of science and medicine in sport*, *18*(6), 697–703. https://doi.org/10.1016/j.jsams.2014.09.007

Vandenberg, S. G., & Kuse, A. R. (1978). Mental rotations, a group test of three-dimensional spatial visualization. *Perceptual and Motor Skills*, *47*(2), 599–604. https://doi.org/10.2466/pms.1978.47.2.599

von Hofsten, C., & Spelke, E. S. (1985). Object perception and object-directed reaching in infancy. *Journal of experimental psychology. General*, *114*(2), 198–212. https://doi.org/10.1037/0096-3445.114.2.198

Von Hofsten, C. (1986). Early spatial perception taken in reference to manual action. *Acta Psychologica*, *63*(4), 323–335. https://doi.org/10.1016/0001-6918(86)90077-6

Von Hofsten, C. (2004). An action perspective on motor development. *Trends in cognitive sciences*, *8*(6), 266–272. https://doi.org/10.1016/j.tics.2004.04.002

Von Hofsten, C. (2009). Action, the foundation for cognitive development. *Scandinavian Journal of Psychology*, *50*(6), 617–623. https://doi.org/10.1111/j.1467-9450.2009.00780.x

Von Hofsten, C., Kochukhova, O., & Rosander, K. (2007). Predictive tracking over occlusions by 4-month-old infants. *Developmental science*, *10*(5), 625–640. https://doi.org/10.1111/j.1467-7687.2007.00604.x

Voyer, D. (1997). Scoring procedure, performance factors, and magnitude of sex differences in spatial performance. *The American Journal of Psychology*, *110*(2), 259. https://doi.org/10.2307/1423717

Voyer, D., Nolan, C., & Voyer, S. (2000). The relation between experience and spatial performance in men and women. *Sex Roles*, *43*(11-12), 891–915. https://doi.org/10.1023/A:1011041006679

Wai, J., Lubinski, D., & Benbow, C. P. (2009). Spatial ability for stem domains: Aligning over 50 years of cumulative psychological knowledge solidifies its importance. *Journal of Educational Psychology*, *101*(4), 817–835. https://doi.org/10.1037/a0016127

Wang, S., Hu, Y., Wang, Q., Wu, B., Shen, Y., & Carr, M. (2020). The development of a multidimensional diagnostic assessment with learning tools to improve 3-d mental rotation skills. *Frontiers in psychology*, *11*, 305. https://doi.org/10.3389/fpsyg.2020.00305

Weber, A. M., Bobrowicz, K., Greiff, S., & Leuchter, M. (2024). Mental rotation is supported by block play in boys and girls. *Journal of Applied Developmental Psychology*, *91*, 101630. https://doi.org/10.1016/j.appdev.2023.101630

Wentworth, N., & Haith, M. M. (1992). Event-specific expectations of 2- and 3-month-old infants. *Developmental Psychology*, *28*(5), 842–850. https://doi.org/10.1037//0012-1649.28.5.842

Wentworth, N., Haith, M. M., & Hood, R. (2002). Spatiotemporal regularity and interevent contingencies as information for infants' visual expectations. *Infancy*, *3*(3), 303–321. https://doi.org/10.1207/S15327078IN0303_2

Wexler, M., Kosslyn, S. M., & Berthoz, A. (1998). Motor processes in mental rotation. *Cognition*, *68*(1), 77–94. https://doi.org/10.1016/S0010-0277(98)00032-8

Wiedenbauer, G., & Jansen-Osmann, P. (2008). Manual training of mental rotation in children. *Learning and Instruction*, *18*(1), 30–41. https://doi.org/10.1016/j.learninstruc.2006.09.009

Wiedenbauer, G., Schmid, J., & Jansen-Osmann, P. (2007). Manual training of mental rotation. *European Journal of Cognitive Psychology*, *19*(1), 17–36. https://doi.org/10.1080/09541440600709906

Witherington, D. C. (2005). The development of prospective grasping control between 5 and 7 months: A longitudinal study. *Infancy*, *7*(2), 143–161. https://doi.org/https://doi.org/10.1207/s15327078in0702_22

Witherington, D. C., Campos, J. J., Anderson, D. I., Lejeune, L., & Seah, E. (2005). Avoidance of heights on the visual cliff in newly walking infants. *Infancy*, *7*(3), 285–298. https://doi.org/10.1207/s15327078in0703_4

Witherington, D. C., & Margett, T. E. (2011). How conceptually unified is the dynamic systems approach to the study of psychological development? *Child Development Perspectives*, *5*(4), 286–290. https://doi.org/10.1111/j.1750-8606.2011.00211.x

Wohlschläger, A. (2001). Mental object rotation and the planning of hand movements. *Perception & psychophysics*, *63*(4), 709–718. https://doi.org/10.3758/bf03194431

Wohlschläger, A., & Wohlschläger, A. (1998). Mental and manual rotation. *Journal of Experimental Psychology: Human Perception and Performance*, *24*(2), 397–412. https://doi.org/10.1037//0096-1523.24.2.397

Wu, D., Yang, J., Xie, S., Luo, J., Chang, C., & Li, H. (2020). An fnirs examination of the neural correlates of mental rotation in preschoolers. *Human Behaviour and Brain*. https://doi.org/10.37716/HBAB.2020010201

Yee, E., Chrysikou, E. G., Hoffman, E., & Thompson-Schill, S. L. (2013). Manual experience shapes object representations. *Psychological science*, *24*(6), 909–919. https://doi.org/10.1177/0956797612464658

Yildiz, R., Yildiz, A., Zorlular, R., & Elbasan, B. (2024). Relationship between sensory processing skills and motor skills in 12-month-old infants. *Brain and behavior*, *14*(9), e70052. https://doi.org/10.1002/brb3.70052

Yonas, A., & Granrud, C. E. (2006). Infants' perception of depth from cast shadows. *Perception & psychophysics*, *68*(1), 154–160. https://doi.org/10.3758/bf03193665

Yonas, A., Granrud, C. E., Arterberry, M. E., & Hanson, B. L. (1986). Infants' distance perception from linear perspective and texture gradients. *Infant Behavior and Development*, *9*(3), 247–256. https://doi.org/10.1016/0163-6383(86)90001-9

Yuniarwati, W., & Lin, L. (2025). Eye-hand coordination performance among preschool children: Fine motor and visual-motor integration. *Hong Kong Journal of Paediatrics*, *30*(3), 104–110.

Zacks, J. M. (2008). Neuroimaging studies of mental rotation: A meta-analysis and review. *Journal of cognitive neuroscience*, *20*(1), 1–19. https://doi.org/10.1162/jocn.2008.20013

Zafeiriou, D. I. (2004). Primitive reflexes and postural reactions in the neurodevelopmental examination. *Pediatric Neurology*, *31*(1), 1–8. https://doi.org/10.1016/j.pediatrneurol.2004.01.012

Zeng, N., Ayyub, M., Sun, H., Wen, X., Xiang, P., & Gao, Z. (2017). Effects of physical activity on motor skills and cognitive development in early childhood: A systematic review. *BioMed research international*, *2017*, 2760716. https://doi.org/10.1155/2017/2760716

Zimmer, T., & Volkamer, M. (1987). MOT - Motoriktest für 4–6 jährige Kinder.

Appendix

Appendix A: Age-Adjusted MR Video Task Randomisation (Study 1)

Table A.1: Trial overview of R-object: Overview of trial order, angle, correct response position

Trial No.	**Angle**	**Correct Response Position**
Trials With Feedback		
1	0°	Left
2	359°	Right
3	299.25°	Right
4	179.5°	Left
5	239.5°	Left
Trials Without Feedback		
6	0°	Right
7	299.25°	Left
8	179.5°	Right
9	239.5°	Right
10	359°	Left

Note. The trial order when the R-object was shown as familiarization video. Correct response position indicates the side (Left or Right) of the target object. Feedback was provided for trials 1-5 and trials 6-10 were without feedback.

Table A.2: Trial overview of L-object: Overview of trial order, angle, correct response position

Trial No.	**Angle**	**Correct Response Position**
Trials With Feedback		
1	120°	Right
2	359°	Left
3	299.25°	Left
4	179.5°	Right
5	239.5°	Right
Trials Without Feedback		
6	0°	Right
7	299.25°	Right
8	179.5°	Left
9	239.5°	Left
10	359°	Right

Note. The trial order when the L-object was shown as familiarization video. Correct response position indicates the side (Left or Right) of the target object. Feedback was provided for trials 1-5 and trials 6-10 were without feedback.

Appendix B: Age-adjusted MR Block Task Randomisation Plans (Study 2)

Table A.3: Randomisation 1 (L- Box): Trial overview of the MR Block task with stimulus presentation with L-Box and correct response position

Trial	**L-object (tester view)**	**Box**	**Correct answer (child view)**	**Angle**
Practice	LEFT	T- Box (1)	RIGHT	0° (X)
Practice	RIGHT	T- Box (1)	LEFT	0° (Y)
1	RIGHT (B)	L-Box (1)	LEFT	0° (X)
2	LEFT (A)	L-Box (1)	RIGHT	45° (Y)
3	LEFT (A)	L-Box (1)	RIGHT	135° (X)
4	RIGHT (B)	L-Box (1)	LEFT	90° (X)
5	RIGHT (B)	L-Box (1)	LEFT	180° (Y)
6	LEFT (A)	L-Box (1)	RIGHT	45° (X)
7	RIGHT (B)	L-Box (1)	LEFT	135° (Y)
8	LEFT (A)	L-Box (1)	RIGHT	90° (Y)
9	RIGHT (B)	L-Box (1)	LEFT	0° (Y)
10	LEFT (A)	L-Box (1)	RIGHT	180° (X)

Note: The test object was the L- object; the test object column refers to its position (A = Left side, B = Right side). The box column indicates the box type (1 = L-Box). For the practice trials, the T-box (denoted with 1) was used. The angle of rotation is indicated in the last column with X and Y being the two axis of rotation.

Table A.4: Randomisation 2 (R-Box): Trial overview of the MR Block task with stimulus presentation with R-Box and correct responses

Trial	**L-object (tester view)**	**Box**	**Correct answer (child view)**	**Angle**
Practice	+ LEFT	+-Box (2)	RIGHT	0° (X)
Practice	+ RIGHT	+-Box (2)	LEFT	0° (Y)
1	LEFT (A)	⅃-Box (2)	LEFT	0° (X)
2	RIGHT (B)	⅃-Box (2)	RIGHT	45° (Y)
3	RIGHT (B)	⅃-Box (2)	RIGHT	135° (X)
4	LEFT (A)	⅃-Box (2)	LEFT	90° (X)
5	LEFT (A)	⅃-Box (2)	LEFT	180° (Y)
6	RIGHT (B)	⅃-Box (2)	RIGHT	45° (X)
7	LEFT (A)	⅃-Box (2)	LEFT	135° (Y)
8	RIGHT (B)	⅃-Box (2)	RIGHT	90° (Y)
9	LEFT (A)	⅃-Box (2)	LEFT	0° (Y)
10	RIGHT (B)	⅃-Box (2)	RIGHT	180° (X)

Note: The test object was the R-object. The box column indicates the box type (2 = R-Box, with an inverted L cutout). For the practice trials, the +-box (denoted with 2) was used. The angle of rotation is indicated in the last column with X and Y being the two axis of rotation.

Table A.5: Randomisation 3 (L-Box): Trial overview of the MR Block task with stimulus presentation with L-Box and correct responses

Trial	**L-object (tester view)**	**Box**	**Correct answer (child view)**	**Angle**
Practice	RIGHT	T-Box (1)	LEFT	0° (X)
Practice	LEFT	T-Box (1)	RIGHT	0° (Y)
1	LEFT (A)	L-Box (1)	RIGHT	0° (X)
2	RIGHT (B)	L-Box (1)	LEFT	45° (Y)
3	RIGHT (B)	L-Box (1)	LEFT	135° (X)
4	LEFT (A)	L-Box (1)	RIGHT	90° (X)
5	LEFT (A)	L-Box (1)	RIGHT	180° (Y)
6	RIGHT (B)	L-Box (1)	LEFT	45° (X)
7	LEFT (A)	L-Box (1)	RIGHT	135° (Y)
8	RIGHT (B)	L-Box (1)	LEFT	90° (Y)
9	LEFT (A)	L-Box (1)	RIGHT	0° (Y)
10	RIGHT (B)	L-Box (1)	LEFT	180° (X)

Note: The test object was the L-object; The box column indicates the box type (1 = L-Box). For the practice trials, the T-box (denoted with 1) was used. The angle of rotation is indicated in the last column with X and Y being the two axis of rotation.

Table A.6: Randomisation 4 (R-Box): Trial overview of the MR Block task with stimulus presentation with L-Box and correct responses

Trial	**L-object (tester view)**	**Box**	**Correct answer (child view)**	**Angle**
Practice	+ RIGHT	+-Box (2)	LEFT	0° (X)
Practice	+ LEFT	+-Box (2)	RIGHT	0° (Y)
1	RIGHT (A)	⅃-Box (2)	RIGHT	0° (X)
2	LEFT (B)	⅃-Box (2)	LEFT	45° (Y)
3	LEFT (B)	⅃-Box (2)	LEFT	135° (X)
4	RIGHT (A)	⅃-Box (2)	RIGHT	90° (X)
5	LEFT (A)	⅃-Box (2)	RIGHT	180° (Y)
6	LEFT (B)	⅃-Box (2)	LEFT	45° (X)
7	RIGHT (A)	⅃-Box (2)	RIGHT	135° (Y)
8	LEFT (B)	⅃-Box (2)	LEFT	90° (Y)
9	RIGHT (A)	⅃-Box (2)	RIGHT	0° (Y)
10	LEFT (B)	⅃-Box (2)	LEFT	180° (X)

Note: The test object was the R-object; the L-object column refers to L-object position (A = Left side, B = Right side); The box column indicates the box type (2 = R-Box, with an inverted L cutout). For the practice trials, the +-box (denoted with 2) was used. The angle of rotation is indicated in the last column with X and Y being the two axis of rotation.

List of Publications and Contributions

Publications (Peer-reviewed journals)

1. **Asokan, T.**, Gehb, G., Jovanovic, B., & Schwarzer, G. (under review). Mental rotation of 3D objects is linked to motor skills in preschoolers. *European Journal of Developmental Psychology.* (PsyArXiv Preprint: https://doi.org/10.31234/osf.io/5kz2t_v1).

2. **Asokan, T.**, Jovanovic, B. & Schwarzer, G. (under review). Role of Motor Skills in Mental Rotation Abilities from Infancy to Preschool Age: A Longitudinal Study. *Acta Psychologica* (PsyArXiv Preprint:https://doi.org/10.31234/osf.io/jh86c)

Poster Contributions (Peer-reviewed Conferences/ Retreats)

1. **Asokan, T.**, Grab, A., Schuler, R., Jovanovic, B., & Schwarzer, G. (2025). Development of Visuospatial Prediction Abilities and Motor Skills in Preterm and Full-Term Infants. *SFB Retreat, Rauischholzhausen, Marburg, Germany*

2. **Asokan, T.**, Grab, A., Schuler, R., Jovanovic, B., & Schwarzer, G. (2025). Developmental Differences in Visuospatial Predictive Abilities in Preterm and Full-Term Infants: The Role of Motor Skills. *Die 26. Tagung der Fachgruppe Entwicklungspsychologie (EPSY), Gießen, Germany*

3. **Asokan, T.**, Jovanovic, B., & Schwarzer, G. (2025). Link between Mental Rotation Ability and Motor Skills from Infancy to Preschool Years. *The Society for Research in Child Development (SRCD), Minneapolis, United States of America.*

4. **Asokan, T.**, Jovanovic, B., & Schwarzer, G. (2025). Motor Skills Contribute to the Development of Mental Rotation from Infancy to Preschool Age. *Tagung experimentell arbeitender Psycholog:innen (TeaP), Frankfurt, Germany.*

5. Grab, A., **Asokan, T.**, Jovanovic, B., Schwarzer, G., Schuler, R., Laffolie, J. (2025). Development of visual-predictive abilities and motor skills in full-term

and preterm infants. *Tagung experimentell arbeitender Psycholog:innen (TeaP), Frankfurt, Germany.*

6. **Asokan, T.**, Jovanovic, B., Schwarzer, G. (2024). Mental Rotation Ability from Infancy to Early Childhood: A Longitudinal Study. *The International Congress for Infant Studies (ICIS), Glasgow, United Kingdom.*

7. **Asokan, T.**, Gehb, G., Jovanovic, B., Schwarzer, G. (2023). Relationship between Mental Rotation Ability and Motor Skills in 4- to 6-year-old children. *The Centre of Mind, Brain and Behaviour (CMBB) Day, Justus Liebig University Giessen.*

8. **Asokan, T.**, Jovanovic, B., Schwarzer, G. (2023). Mental Rotation Abilities and Motor Skills in 4- to 6-year-Old Children. *SFB Retreat, Rauischholzhausen, Marburg, Germany*

9. **Asokan, T.**, Gehb, G., Jovanovic, B., Schwarzer, G. (2023). Development of Mental Rotation Abilities and Motor Skills in 4-to-6-year-old Children. Die 25. *Tagung der Fachgruppe Entwicklungspsychologie (EPSY), Berlin, Germany*

Talks (Peer-reviewed/Invited)

1. **Asokan, T.** & Schwarzer, G. (2026). The Role of Motor Skills in the Development of 3D Mental Rotation from Infancy to Preschool. *Budapest CEU Conference on Cognitive Development (BCCCD), Budapest, Hungary*

2. **Asokan, T.**, Lüthgen, A., Jovanovic, B., Schwarzer, G. (2024). Development of Visual-Spatial Predictive Abilities and Motor Skills in Preschoolers.*SFB Retreat, Rauischholzhausen, Marburg, Germany*

3. **Asokan, T.**, Gehb, G., Jovanovic, B., Schwarzer, G. (2024). Mental Rotation Ability and Motor Skills in Early Childhood. *Tagung experimentell arbeitender Psycholog:innen (TeaP), Regensburg, Germany.*

4. **Asokan, T.** (2024) Development of Mental Rotation Ability and Motor Skills in Early Childhood. *Invited Talk, Winter Colloquium, University of Regensburg, Germany*