CHAPTER ONE

The development of mental rotation ability across the first year after birth

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Abstract

Mental rotation (MR) is the ability to imagine the appearance of an object from a different perspective. This ability is involved in many human cognitive and behavioral activities. We discuss studies that have examined MR in infants and its development across the first year after birth. Despite some conflicting findings across these studies, several conclusions can be reached. First, MR may be available to human infants as young as 3 months of age. Second, MR processes in infancy may be similar or identical to MR processes later in life. Third, there may be sex differences in MR performance, in general favoring males. Fourth, there appear to be multiple influences on infants' MR performance, including infants' motor activity, stimulus complexity, hormones, and parental attitudes. We conclude by calling for additional research to examine more carefully the causes and consequences of MR abilities early in life.

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Mental rotation (MR) refers to the ability to imagine how an object that has been seen from one perspective would look if it were rotated in space into a new orientation and viewed from the new perspective. Often without knowing it, people use this spatial-cognitive ability in a wide variety of situations. MR can be useful when deciding which way to turn at an intersection after using a paper map to navigate (Kerkman, Wise, & Harwood, 2000; Levine, Huttenlocher, Taylor, & Langrock, 1999), when designing a building (i.e., in the field of architecture), when performing laparoscopic surgery (Conrad et al., 2006), when trying to visualize the three-dimensional structures of complex molecules, when learning to read (as we discriminate between b, p, q, and d; for example, see Rusiak, Lachmann, Jaskowski, & van Leeuwen, 2007; Rüsseler, Scholz, Jordan, & Quaiser-Pohl, 2005), and in several other disciplines related to science, technology, engineering, and mathematics (Shea, Lubinski, & Benbow, 2001; Wai, Lubinski, & Benbow, 2009). MR has been linked to competent performance in geometry (Newcombe, Booth, & Gunderson, 2019) and to mathematical competence more generally (Frick, 2019; Lauer & Lourenco, 2016; van Tetering, van der Donk, de Groot, & Jolles, 2019; Verdine, Golinkoff, Hirsh-Pasek, & Newcombe, 2017; Young, Levine, & Mix, 2018). Because of its importance in human activities, therefore, MR has been the subject of extensive research.

By the late 19th century, Francis Galton had started studying how people visualize previously encountered scenes (Galton, 1880), and interest in mental imagining abilities grew in the early 20th century (Thurstone, 1938). Nonetheless, it was not until the 1970s that the modern study of MR began. In that decade, Roger Shepard (Shepard, 1978; Shepard & Metzler, 1971) published the results of a series of studies that used chronometric methods to examine adults' ability to mentally rotate representations of 3-dimensional (3D) objects. A key finding in this seminal research was that the amount of time it takes people to mentally rotate a representation of a 3D object is a linear function of the angle through which the represented object is being rotated. That is, it takes longer to recognize a previously seen object when it has been rotated through, say, a 160-degree angle than when it has been rotated through an 80-degree angle. This result was taken to support the claim that people engaging in MR are utilizing analog spatial representations. The idea that Shepard's chronometric data supported the existence of actual mental images struck some observers as intuitively reasonable, and subsequent studies provided neuroscientific evidence that supported this idea (e.g., see Kosslyn, 1994). Nonetheless, the idea that people can perform some cognitive operations using analog mental images continued to generate controversy into the 21st century (Pylyshyn, 2002).

In the decades that followed Shepard's pioneering work in this domain, hundreds of studies of mental rotation were conducted. These studies generated numerous findings, including that MR is accompanied by increased activity in and around the brain's intraparietal sulcus and in the medial superior pre-central cortex (Zacks, 2008), that MR in some situations depends on mental simulation of motor processes (Amorim, Isableu, & Jarraya, 2006; Kosslyn, Digirolamo, Thompson, & Alpert, 1998; Krüger, Amorim, & Ebersbach, 2014; Krüger & Ebersbach, 2018; Sekiyama, 1982), and that MR performance is influenced by circulating sex hormones (Aleman, Bronk, Kessels, Koppeschaar, & van Honk, 2004; Hampson, 2018; Hausmann, Slabbekoorn, Van Goozen, Cohen-Kettenis, & Güntürkün, 2000) as well as exposure to sex hormones early in development (Alexander & Son, 2007; Falter, Arroyo, & Davis, 2006; Grimshaw, Sitarenios, & Finegan, 1995). In addition, numerous studies have demonstrated that MR performance can be improved with training (Baenninger & Newcombe, 1989; Cherney, Jagarlamudi, Lawrence, & Shimabuku, 2003; Fernández-Méndez, Contreras, & Elosúa, 2018; Sanz de Acedo Lizarraga & García Ganuza, 2003).

Among these discoveries has been the unexpected finding that there is a relatively strong sex difference in performance on MR tasks (Linn & Petersen, 1985; Schöning et al., 2007; Voyer, Voyer, & Bryden, 1995): on average, male participants outperform female participants. For example, Kail, Carter, and Pellegrino (1979) reported that nearly one-third of their 53 female participants rotated visual stimuli more slowly than the very slowest male participant in the group of 51 they tested. In fact, a large meta-analysis of studies on spatial-cognitive ability reported that the most significant sex differences were found on tasks requiring MR (Voyer et al., 1995). For tasks involving the MR of representations of 3D objects through 3D space, the effect sizes associated with the sex difference are typically large, and larger than the effects of sex on most other types of behavior, including rough-and-tumble play in childhood and aggressive behavior more generally (Collaer & Hines, 1995). The sex difference in MR performance is the largest and one of the most robust of all cognitive sex differences (Linn & Petersen, 1985; Voyer et al., 1995).

Despite this growing pool of information, studies on the *development* of MR in very young children and infants have only begun to accumulate in the past decade. While the first evidence of MR in 5-year-olds emerged shortly after Shepard and Metzler's groundbreaking work (Marmor, 1975)—and dozens of studies on the development of MR in children between 4 years of age and adolescence have now been conducted (e.g., Estes, 1998; Iachini, Ruggiero, Bartolo, Rapuano, & Ruotolo, 2019; Kail, 1986, 1991; Kail, Pellegrino, & Carter, 1980; Moè, 2016; Titze, Jansen, & Heil, 2010; van Tetering et al., 2019)—several studies failed to find evidence that children *younger* than 5 years of age are capable of MR (see, e.g., Krüger, Kaiser, Mahler, Bartels, & Krist, 2014). Some research has suggested that any failures to detect MR in preschoolers might reflect a lack of ability, rather than the questionable use of tests meant to evaluate older populations (Frick, Ferrara, & Newcombe, 2013; Quaiser-Pohl, Rohe, & Amberger, 2010); this conclusion is consistent with earlier thinking about the developmental emergence of this competence. However, other studies have demonstrated that when the task used to evaluate MR is appropriately simplified for very young children, even 3- and 4-year-olds are able to provide evidence of MR (Frick, Hansen, & Newcombe, 2013; Krüger, 2018; Krüger et al., 2014; Levine et al., 1999).

Further discussion of the development of MR in preschool-aged children is beyond the scope of this chapter, but it is worth noting that in this age range, no consistent pattern of sex differences in MR competence has emerged. Voyer and colleagues' meta-analysis (1995) included only four studies of children under the age of 10 years, and three of these studies reported no effects of sex. As a result, these authors concluded that sex differences in MR do not emerge prior to about 10 years of age. Consistent with this conclusion, neither Krüger (2018) nor Krüger et al. (2014) observed sex differences in their preschool-aged research participants. In contrast, Levine et al. (1999) reported a substantial advantage for male over female 4.5-year-olds on a spatial transformation task, which included both rotation and translation items, and Frick, Hansen, and Newcombe (2013) reported some sex differences as well with 3-year-old participants. Nonetheless, the sex differences in the latter study were inconsistent, with 3-year-old girls having an advantage in some conditions and 3-year-old boys having an advantage in other conditions. Consequently, the existence of a sex difference in MR competence in children in this age range remains an open question.

1. Initial studies of MR in infants

Studies of MR in children, adolescents, and adults have taken advantage of the fact that these research participants can understand verbal instructions and generate verbal responses. Unfortunately, researchers studying nonverbal individuals such as infants do not have access to these competencies in their research participants and have consequently needed to develop creative ways to obtain their data. Because of this limitation, studies of MR in infants lag behind studies of MR in older populations.

1.1 Forerunners of research on MR in infants

Prior to the first reports of evidence of MR in infants, some researchers had conducted studies that presented infants with rotating objects as visual stimuli; although these studies did not purport to examine MR per se, they generated findings that helped set the stage for research on the development of MR in infancy. For example, using rotating object stimuli, Kellman (1984) established that 4-month-olds can detect the 3D form of objects rotating around two different axes of rotation (see also Kellman & Short, 1987). Later studies revealed that 2-month-olds presented with kinetic random-dot video displays that specify rotating 3D cubes can perceive the 3D shape of such objects (Arterberry & Yonas, 2000), that 2-month-olds who see video displays of partially occluded 3D shapes rotating around a vertical axis can perceive the unity of the displayed objects despite the presence of the occluders (Johnson, Cohen, Marks, & Johnson, 2003), and that infants between 3 and 5 months of age can recognize objects when multiple views of those objects have been provided (Kraebel & Gerhardstein, 2006; Mash, Arterberry, & Bornstein, 2007), even by rotating the objects around orthogonal axes of rotation (Mash et al., 2007). Nonetheless, the results of these studies were not presented as evidence of MR in infants. In contrast, after demonstrating that 4-month-olds can form dynamic mental representations that allow them to anticipate a rotating object's ultimate orientation, Rochat and Hespos concluded that they had uncovered "the first evidence of some rudiments of mental rotation in infancy" (Rochat & Hespos, 1996, p. 3). On the heels of their initial report in 1996, Hespos and Rochat (1997) published a series of follow-up studies that further explored this phenomenon.

In both their initial report and their follow-up studies, these researchers utilized a violation-of-expectation (VoE) method to generate their data. The VoE method relies on the assumption that infants will look longer at visual displays that *violate* their expectations than they will look at visual displays that *confirm* their expectations. As represented in Fig. 1, Rochat and Hespos (1996) tested infants as young as 4 months of age with a two-dimensional (2D) object that underwent rotational motion through a 180-degree arc in the frontal plane. Once the object rotated through approximately 120 degrees of arc it was seen to rotate behind an occluding screen. After the infants saw the object disappear behind the occluder, the

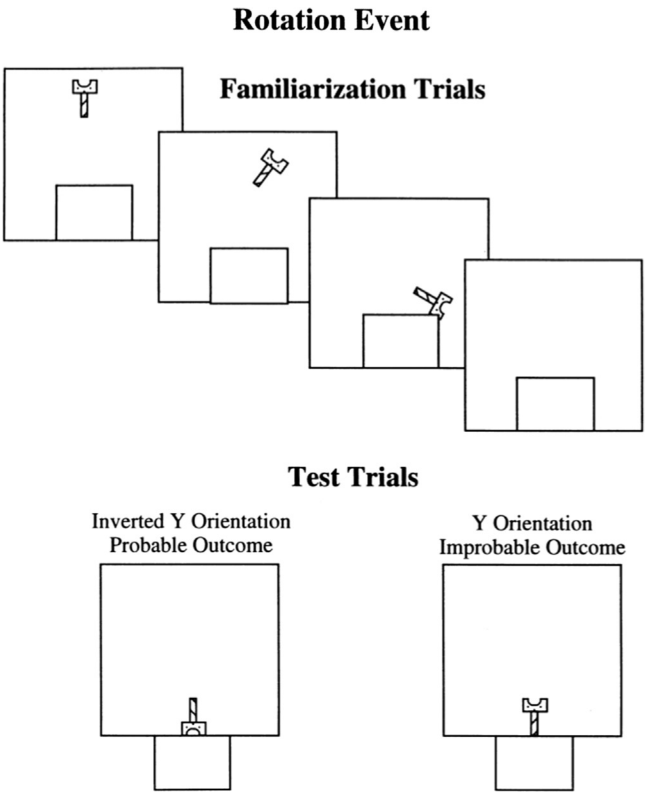

Fig. 1 Schematic depiction of the rotational event presented to infants. *Adapted from Hespos, S. J., & Rochat, P. (1997). Dynamic mental representation in infancy.* Cognition, *64, 153–188; fig. 2B.*

screen was lowered to reveal the object. In half of the subsequent test trials, the infants saw the object in the orientation that an adult observer would expect it to be in if they had tracked the object successfully through its rotational motion behind the occluder. In the other half of the test trials, the infants saw the object in an inverted orientation (achieved by a bit of clandestine trickery on the part of the experimenters). Because the infants looked at the inverted object significantly longer than they looked at the un-inverted object—presumably because their expectations about its final orientation had been violated—the researchers concluded that infants as young as 4 months can *anticipate* the orientation of an object undergoing rotational motion behind an occluder. Rochat and Hespos considered this to be evidence of rudimentary MR in young infants. We are not aware of any other studies of MR in infants that were published between Hespos and

Rochat's (1997) study and our first study of MR in infants, which was published more than a decade later (Moore & Johnson, 2008), and which is described next.

1.2 First studies of MR in infants

The Moore and Johnson (2008) study differed from prior studies in three important ways. First, infants in this study saw video images of 3D stimulus objects rotating in 3D space around a vertical axis. This distinction is potentially important, as the largest effects of sex on older participants' MR performances have been observed in tasks requiring the rotation of 3D objects through 3D space (Hines, 2013; Levine et al., 1999; Linn & Petersen, 1985; Voyer et al., 1995). Second, Moore and Johnson used a habituation paradigm rather than a VoE paradigm. Habituation paradigms rely on the established fact that after repeated exposure to almost any stimulus, infants will exhibit a reduced response to that stimulus, but will continue responding at baseline levels to novel stimuli. Therefore, differential looking times to novel versus familiar stimuli in habituation studies can confidently be ascribed to discrimination and at least some level of recognition (Fantz, 1964). In contrast, the VoE method normally entails an inference that increased looking reflects *expectations*, a prospect that is difficult to confirm independently and that has therefore been criticized by numerous theorists (Bogartz, Shinskey, & Schilling, 2000; Cashon & Cohen, 2000; Charles & Rivera, 2009; Haith, 1998; Kagan, 2019; Moore & Cocas, 2006). Finally, infants in the Moore and Johnson study were required to discriminate between an object and its mirror image, as older participants are required to do in Shepard-style MR studies (Shepard & Cooper, 1982). Together, these features rendered this study among the first designed specifically to evaluate MR in infants.

The 20 male and 20 female infants tested by Moore and Johnson (2008) were 5 months of age on average and were initially presented with a series of habituation trials that showed a video representation of an unfamiliar 3D object rotating on a monitor screen (see Fig. 2). Each of these habituation trials presented the infant with the identical stimulus: a dynamic, colorful Lego-like block object that was seen rotating back and forth continuously around the vertical axis through a 240-degree arc at a rate of 45 degrees per second. A trained observer, who was blind to the visual stimulus and invisible to the baby, measured the infants' looking times at this display. As expected, these looking times gradually decreased across trials as the infants became habituated to the stimulus. Each trial ended when the infant

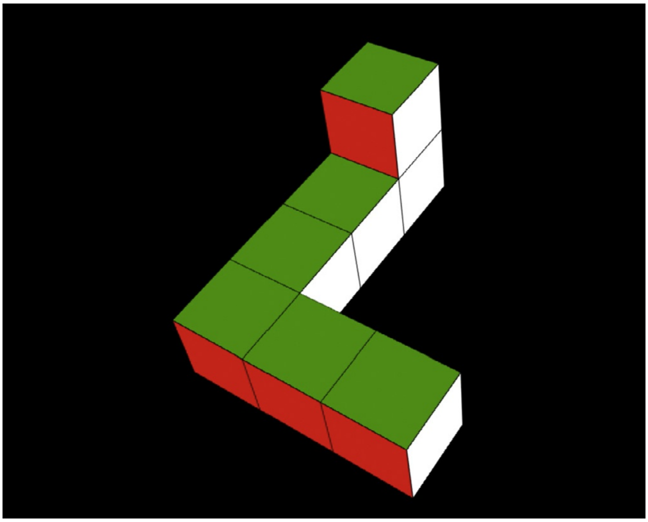

Fig. 2 Stimulus object presented in Moore and Johnson (2008, 2011), as well as in Christodoulou, Johnson, Moore, and Moore (2016), Constantinescu, Moore, Johnson, and Hines (2018), Heil, Krüger, Krist, Johnson, and Moore (2018), and Slone, Moore, and Johnson (2018). In a series of habituation trials, this object—or its mirror-image—was seen rotating back and forth on its vertical axis through a 240-degree angle. After habituation, this object (or its mirror-image) was seen in a series of test trials in which the object was shown rotating back and forth on its vertical axis through the previously unseen 120 degrees of arc. *Adapted from Moore, D. S., & Johnson, S. P. (2008). Mental rotation in human infants: A sex difference.* Psychological Science, 19*, 1063–1066; fig. 1*.

looked away from the display for two consecutive seconds (or after 60 s of continuous looking with only brief looks away [i.e., <2 s] from the display), whereupon the visual stimulus was terminated. Once an infant's looking in a series of four trials declined to half of their looking on the first four trials, the infant was deemed habituated. After infants were habituated (or after 12 habituation trials, whichever came first), they saw a series of six test trials.

Across these test trials, infants saw two different video displays. In one, they saw the same object they had previously seen in the habituation trials, but now rotating back and forth continuously around the vertical axis through the previously unseen 120 degrees of arc. That is, they saw the familiar object, but now only from the "back side" (see Fig. 3A). There were no still frames composing the test video that were identical to any of the still frames composing the habituation video. The other test video showed a mirror-image of the familiar object, also rotating through a 120-degree arc (see Fig. 3B). The objects in these two test videos appeared and behaved

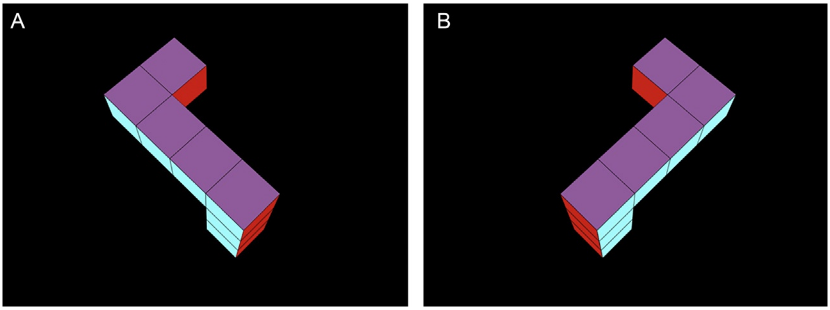

Fig. 3 Stimulus objects presented during test trials in Moore and Johnson (2008, 2011), as well as in Christodoulou et al. (2016), Constantinescu et al. (2018), Heil et al. (2018), and Slone et al. (2018). Following habituation, infants saw either the object pictured in (A) or the object pictured in (B) rotating back and forth on its vertical axis through a never-before-seen 120 degrees of arc. Object (A) represents the "back side" of the habituation object seen in Fig. 2. Object (B) represents the mirror-image of object (A). In Moore and Johnson (2008, 2011), objects (A) and (B) were seen in alternation across a series of six test trials. *Adapted from Constantinescu, M., Moore, D. S., Johnson, S. P., & Hines, M. (2018). Early contributions to infants' mental rotation abilities.* Developmental Science, 21*(4), e12613; fig. 2.*

identically, other than in their left-right orientations. Half of the infants saw the familiar object in the first test trial while the other half saw the mirror-image object in that test trial; these test objects were then presented in alternating test trials until all six test trials had been completed.

Critically, both test images were novel, having never been seen by any infant in this study. Nonetheless, one of the two test objects could have seemed "familiar" to some infants if they recognized it as the same object seen during habituation, albeit from a novel perspective. In contrast, the other test object was completely novel, even though it looked and behaved very much like the familiar object (i.e., in the same way that a person's left and right hands might look very much like one another, even though they are discriminable). As we argued in our 2008 paper, differential looking at the two test objects would necessarily reflect infants' prior experience with the habituation object, because otherwise, there would be no reason for infants to reliably fixate one of these test objects more than the other. Thus, differential looking would suggest that infants recognized the habituation object when it was seen from a novel perspective in the test trials.

To our surprise—because we did not expect to see a sex difference this early in development—male 5-month-olds, on average, looked significantly longer at the mirror-image test object than at the other test object, whereas female 5-month-olds, on average, looked at both test objects for about the same amount of time. Likewise, 70% of the male babies preferred the mirror-image test object whereas only 45% of the female babies did. These differences occurred even though female and male infants took the same amount of time to habituate to the original object. We concluded that the male infants' preferences for the mirror-image test object indicated that they were relatively uninterested in the *other* test object, because they had already become bored of looking at that object during the habituation trials. Note, however, that they behaved in this uninterested manner during the test trials *even though they had never seen the habituation object from the novel test trial perspective*. Thus, they seemed to *recognize* the habituation object when it was seen from this novel perspective. Recognizing the object like this required MR of a representation of the habituation object (so as to allow a comparison of that representation with the visible test object), or MR of a representation of the test object (so as to allow a comparison with a representation of the habituation object), or both.

By coincidence, a paper with a very similar result was published alongside the Moore and Johnson (2008) report in the same issue of *Psychological Science*. Quinn and Liben (2008) reported that in a population of 12 male and 12 female 3- to 4-month-olds, female infants had no visual preference for a novel view of a previously seen object or a mirror-image of that object, but male infants spent significantly more time looking at the mirror-image of the object. In addition, whereas 11 out of 12 male infants looked longer at the mirror-image object, only 5 out of 12 female infants did. Unlike the dynamic 3D stimulus objects employed by Moore and Johnson, however, Quinn and Liben presented infants with a static image of a 2D object during multiple familiarization trials—showing them the object in a new orientation in each subsequent familiarization trial—and they tested infants with an image of the object (and its mirror-image) rotated through 2D space, as if around a clock face (see Fig. 4). These researchers followed up their work 6 years later with an examination of an alternative hypothesis that could have explained their finding without attributing better MR performance to male over female infants. They hypothesized that females may be more sensitive to the angular differences in the familiarized shapes, thus attending to different stimulus attributes than males. However, the follow-up study did not provide support for the alternative hypothesis (Quinn & Liben, 2014), therefore strengthening confidence in the initial conclusions. In a second study that used the same procedure used in their original study, Quinn and Liben (2014) demonstrated a male advantage in two older age groups, 6- to 7-month-olds and 9- to 10-month-olds.

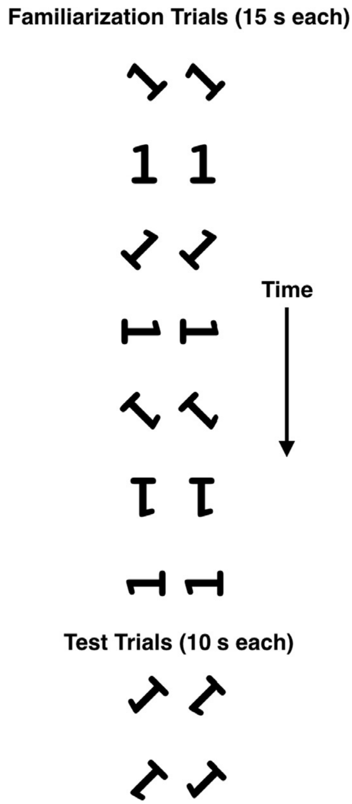

Fig. 4 Schematic depiction of the experimental design implemented by Quinn and Liben (2008). As described by Quinn and Liben (p. 1068), "infants were presented with seven different rotations of the number 1 stimulus (or its mirror image) during familiarization, with two identical copies of each stimulus presented on each trial. For familiarization, [Quinn & Liben] randomly selected seven of the eight possible rotations and their order of presentation for each infant in the female group and a corresponding infant in the male group. The test stimuli paired the novel rotation of the familiar stimulus with its mirror image." *Adapted from Quinn, P. C., & Liben, L. S. (2008). A sex difference in mental rotation in young infants.* Psychological Science, 19*, 1067–1070; fig. 2*.

2. Further evidence of the emergence of MR in infancy

To the best of our knowledge, no one has yet reported evidence of MR before 3 months after birth. However, since 2008, a small but growing number of published studies have reported on MR in infants between the ages of 3 and 10 months. These studies have addressed several questions, and they have yielded tentative answers in some cases and engendered controversy in others. Perhaps the most central question is about whether we can be confident that MR competence emerges in infancy. A second question that has generated much interest is about the possible existence of a sex difference in MR competence in infancy. A third question is about antecedent factors that might contribute to the development of this important skill. We will consider each of these questions in turn in the pages that follow.

Several different methods used by researchers in several different laboratories have now provided converging evidence that MR processes can be detected in infants. This discovery has sometimes been overshadowed by controversy surrounding the existence of a sex difference in MR competence, but it is important not to lose sight of it. Prior to 2008, the suggestion that infants could be capable of MR might have been met by shrugs of ignorance or by outright skepticism. But if in fact the scientific community ultimately converges on the idea that this unique skill develops in the first 3 months after birth, interventions designed to improve competence in this domain could be implemented at an appropriately early stage.

In 2011, we published a follow-up to our 2008 study, which used identical methods and stimuli but with a population of 20 male and 20 female 3-month-olds. This study revealed a sex difference in younger infants as well (Moore & Johnson, 2011). Once again, female infants looked at the two test stimuli for about the same amount of time, but the 3-month-old male infants looked longer at the habituation object in the new orientation than they did at the mirror-image object. By employing a model advanced by Hunter, Ames, and Koopman (1983), we concluded that the MR task was more difficult for the younger infants than it was for the older infants. Hunter and colleagues successfully explained some variation in infants' looking times by positing that their fixation durations are affected by factors such as familiarization time, stimulus complexity, and the infants' ages. More specifically, they argued that familiarity preferences are more likely than novelty preferences when infants have not finished processing a stimulus. Consequently, if a stimulus is complex, if an infant is young (and therefore less able to process information quickly), or if an infant is exposed to a stimulus for a relatively short period of time, that infant will be more likely to fixate a familiar, but incompletely processed, stimulus than a novel stimulus (Hunter & Ames, 1988). This perspective is consistent with that of Colombo (1995), who noted that infants look longer when slower processing speeds lead them to require more time to look at and process information about stimulus properties.

Because the 3-month-old males in the Moore and Johnson (2011) study demonstrated a statistically reliable preference for the familiar test stimuli, they—like the 5-month-olds in the Moore and Johnson (2008) study—did not treat the test stimuli equivalently, as they would have done if they failed to recognize the habituation object. Thus, we concluded that male 3-month-olds, like male 5-month-olds, are capable of MR, even if their familiarity preference suggested that the task was more difficult for them than it was for the older infants tested in 2008. In addition to allowing the inference that our MR task is more difficult for 3-month-olds than for 5-month-olds, the 3-month-old males' familiarity preference also suggests that our task is more difficult than the Quinn and Liben (2008) task, in which similarly-aged infants showed a novelty preference; this effect could perhaps reflect the fact that while our task requires recognition of a 3D object rotated though 3D space, the Quinn and Liben task requires recognition of a 2D object rotated through 2D space.

In the laboratories that have used the stimuli and methods we used in the Moore and Johnson (2008, 2011) studies—which include our laboratories as well as those of our collaborators in England and Germany—effects suggestive of MR have been detected consistently. For example, a replication of our 2008 study at the University of Cambridge found a significant novelty preference among 5-month-old boys (Constantinescu et al., 2018), and a study in our labs that utilized a two-monitor display—a methodological feature that might arguably have been expected to make the task more difficult—revealed a significant familiarity preference among 5-month-old infants (Christodoulou et al., 2016). Likewise, a large study conducted in Germany found a significant familiarity preference among male and female 5-month-olds tested using our paradigm (Erdmann, Kavšek, & Heil, 2018).

Other researchers have studied babies 6 months of age or older using methods that were similar to ours in some cases and relatively dissimilar in others. In each case, although there was often variation depending on the infants' prior experiences, evidence suggestive of the presence of MR competence was obtained. For instance, using a VoE paradigm, Möhring and Frick (2013) found evidence of MR in 6-month-olds, provided the infants had previously been given an opportunity to manually explore an object before being tested with it. Likewise, Lauer, Udelson, Jeon, and Lourenco (2015) reported that infants as young as 6 months of age can form mental representations of the orientation of a 2D object and use those mental representations to discriminate the object from its mirror image, a finding these researchers considered convergent evidence for MR competence in infancy.

Finally, several studies conducted on slightly older infants have explored the possibility that MR competence in the first year after birth is related to gross motor development. In a study of 9-month-olds using methods similar to ours, Schwarzer, Freitag, Buckel, and Lofruthe (2013) found that performance was related to crawling ability, such that only infants who had started to crawl had a significant preference for the novel, mirror-image test object. In the first of two follow-up studies conducted by Schwarzer and her colleagues, Schwarzer, Freitag, and Schum (2013) confirmed this finding while also discovering that among non-crawling 9-month-olds, only those who spontaneously explored a collection of toy blocks with their hands showed a significant preference for the novel, mirror-image test object. In the second follow-up study, Gerhard and Schwarzer (2018) found that while non-crawling 9-month-olds spent approximately equal amounts of time looking at novel views of familiar and mirror-image test objects, 9-month-olds with crawling experience spent significantly more time looking at the mirror-image object in a condition requiring a small degree of MR, but significantly more time looking at the *familiar* object (seen from a new perspective) in a condition requiring a larger degree of MR. Additional results consistent with these findings were reported by Frick and Möhring (2013), who found that among 10-month-olds, MR performance on a VoE task was related to extent of motor development reported by parents on a questionnaire.[a]

Taken together, this collection of results suggests that at least some infants become capable of MR in the first year after birth. Of course, we do not know if any other researchers have conducted studies like these and found null results that they have not published. A formal meta-analysis of studies of MR in infants might soon be possible, which would allow for an estimation of any such "file drawer problem" (Rosenthal, 1979). But faced with the currently available evidence generated in several different laboratories using several different methodologies in multiple countries, MR competence does appear to emerge in at least some infants by 10 months of age.

One unresolved question is whether the phenomena just reported ought to be considered bona fide evidence of MR (Levine, Foley, Lourenco, Ehrlich, & Ratliff, 2016). As noted previously, MR in adults has traditionally been inferred from chronometric data revealing that it takes longer for people to mentally rotate an object through a larger angle than a smaller angle,

[a] In contrast to these results, Erdmann et al. (2018) found no effect of crawling on MR ability. Note, however, that these researchers were also unable to find evidence of MR ability at all in 9-month-old infants.

but very few studies of MR in infants have manipulated the angle through which MR is required. Although the three studies we know of that have manipulated this angle found evidence that was either consistent (Gerhard & Schwarzer, 2018) or not inconsistent (Frick & Möhring, 2013; Möhring & Frick, 2013) with genuine MR, no studies of infants have reported chronometric data that are directly analogous to the kind of chronometric data that proved convincing in the original studies of MR in adults. Researchers have not yet invented a method that can yield this sort of data in infants, who are nonverbal and unable to follow explicit instructions. And in the absence of such data, it remains possible that infants' behaviors might best be explained by referring to competences other than MR.

For instance, in protocols that involve habituation and test videos containing frames that show an object from similar (although non-identical) perspectives, it is possible that infants' memory of a frame from a habituation video might be indiscriminable from their experience of an adjacent frame from a test video, in which case their behavior on test trials would be evidence of poor discrimination rather than MR. In addition, while tests of MR in older populations typically require participants to initiate an MR process on their own, many studies of MR in infants involve showing them an already-rotating object, and as Möhring and Frick (2013) pointed out, this might allow infants to merely extrapolate the movement they are seeing rather than initiate a process of MR. Additional studies that vary angles through which MR is required might help address some of these concerns, as might studies that contrast infants' performances when faced with dynamic versus static habituation stimuli.

Another approach that could shed light on the relation between genuine MR in older populations and processes that *appear* to be MR in infants involves tests of older participants. For instance, longitudinal studies can potentially illuminate relationships between the phenomena observed in infancy and clear-cut cases of MR in older populations. Lauer and Lourenco (2016) have already reported one such study. They discovered that infants' performances on a mental spatial transformation task were predictive of mathematical and spatial aptitude at 4 years of age, which is consistent with the contention that tasks for infants involving multiple perspectives of mirror-image objects reflect MR processes. Likewise, this contention was supported by a study that detected the sex difference in MR typically found in adult populations, but using a modified-for-adults, two-alternative forced-choice version of the Moore and Johnson (2008) infant MR task (Heil et al., 2018). In addition, this study detected significant positive correlations (*p*s < 0.001) for both men and women between performance on Vandenberg and Kuse's (1978) pencil-and-paper Mental Rotation Test and performance on the modified version of our MR task for infants. Such findings should increase confidence that our task does assess MR competence per se in infants. Nonetheless, additional research with both infants and older participants could appreciably strengthen the conclusion that infants are capable of genuine MR.

3. Sex differences in MR in infants

As noted earlier, numerous studies of MR in adults have revealed sex differences favoring males, and meta-analyses of studies in this domain have confirmed that when participants are asked to rotate mental representations of 3D objects through 3D space, the magnitude of this sex difference is large and the effect is robust (Linn & Petersen, 1985; Voyer et al., 1995). In contrast, studies of young children have provided less consistent results. Following their 1995 meta-analysis, Voyer and colleagues concluded that a sex difference in MR does not appear prior to about 10 years of age, and more recent research by Krüger (2018) and Krüger et al. (2014) likewise found no sex differences in MR in a population of preschoolers. Some researchers (Frick, Hansen, & Newcombe, 2013; Levine et al., 1999) have reported sex differences in children as young as 3 or 4.5 years of age, but these were inconsistent in direction and across conditions.

Below 1 year of age, the existence of a sex difference in MR ability remains equally uncertain; several studies have found sex differences and several others have not. In part because precursory work in this domain did not reveal any sex differences (Hespos & Rochat, 1997; Mash et al., 2007; Rochat & Hespos, 1996), we did not expect to find sex differences in our first study of MR in infancy. However, as described previously, both of the first studies of MR in infants reported a sex difference favoring males (Moore & Johnson, 2008; Quinn & Liben, 2008). Since then, two additional studies in our labs (Constantinescu et al., 2018; Moore & Johnson, 2011) and three additional studies in the labs of three other teams (Kaaz & Heil, 2019; Lauer et al., 2015; Quinn & Liben, 2014) have reported similar sex differences in infants 10 months of age or younger. In contrast to these seven studies, two studies in our labs (Christodoulou et al., 2016; Slone et al., 2018) and six studies in the labs of three other teams (Erdmann et al., 2018; Frick & Möhring, 2013; Gerhard & Schwarzer, 2018; Möhring & Frick, 2013; Schwarzer, Freitag, Buckel, & Lofruthe, 2013;

Schwarzer, Freitag, & Schum, 2013) have reported no sex differences in infants from this age range. Given this relatively even distribution of findings, we agree with the conclusion offered in Lauer and colleagues' recent meta-analytic review on the development of gender differences in spatial reasoning: "further investigation of infants' mental rotation abilities will be necessary to determine whether gender differences in implicit mental rotation performance are indeed present in the first year of life and, if so, whether these gender differences represent the origins of the later male advantage in explicit mental rotation performance" (Lauer, Yhang, & Lourenco, 2019, p. 550; see also Levine et al., 2016).

Even though it is too early to say with confidence whether sex differences in MR competence are present in the first year after birth, there are some observations worth noting at this juncture. First, although several studies of infants have failed to find evidence of a sex difference in MR competence, those that have found a sex difference have consistently found an advantage for male infants. In six out of seven of these cases, male infants on average have responded in significantly different ways to familiar versus mirror-image objects, whereas female infants on average have consistently treated these objects similarly. Although the data from the seventh study (Lauer et al., 2015) indicated that both male and female infants discriminated non-mirror from mirror-image objects, a main effect of sex still indicated that boys spent significantly more time than girls looking at displays containing mirror-image objects. Thus, in the studies that have detected sex differences to date, all seven have revealed effects in the same direction, in favor of males.

Second, it is important to keep in mind that the absence of data (in 6 out of 7 studies) suggesting that female infants discriminate mirror- from non-mirror-images cannot be taken as conclusive evidence that these infants are *not* capable of MR. As Levine et al. (2016) noted, "There are many reasons why infants may not look longer at the novel mirror image stimulus … they may find both test stimuli interesting—after all, both are presented [from a perspective] that was not seen during the habituation trials. … This possibility would be consistent with a sex difference, but not one that reflects an ability of male but not female infants to mentally rotate figures" (pp. 5–6). In fact, the Lauer et al. (2015) finding that female infants preferred displays containing mirror-images over displays containing only non-mirror-images—albeit significantly less than male infants did—is consistent with the possibility that female infants *are* capable of MR, even if they do not consistently provide evidence of that competence.

Finally, when considering these sorts of findings, it is advisable to remain aware that it is never the case that all male infants outperform all female infants in these sorts of tasks. Instead, the differences reported in the literature are always differences between the *average* behavior of male infants and the *average* behavior of female infants; there is normally considerable overlap between the distributions generated by male and female infants. In addition, while the phrase "sex difference" can be convenient shorthand that we will continue to use in this chapter, it can also lead to essentialist conclusions about male and female infants that are likely unwarranted. As the behavioral neuroendocrinologist Elizabeth Hampson has pointed out, the kinds of differences described in this section might "reflect the operation of graded factors that covary with sex (e.g. ambient hormone concentrations), not sex as a categorical variable. Indeed, sex is frequently only an imperfect proxy for factors such as hormones that explain between-sex and within-sex variation better than binary 'sex' alone" (Hampson, 2018, p. 49).

4. Factors affecting infants' MR performances

At present, we know about only some of the antecedent factors that contribute to the development of MR competence in infancy. Worse still, the mechanisms by which these factors bring about developmental change remain to be elucidated. The few studies of infants that have examined factors related to their MR performances have supported hypotheses about the importance of two specific factors, namely motor development and stimulus or task complexity. In addition, one study that detected sex differences in infants' MR performances provided clues about additional factors that influence the development of MR in infancy, namely hormones and parental attitudes. Finally, given established findings in older populations, we can also speculate about the importance of additional factors, such as training experiences and socialization. We consider each of these factors in turn.

4.1 Motor activity

Shortly after the first reports of MR in infancy, two different teams of researchers provided evidence that infants' performances on an MR task are related to their motor activity. The hypothesis that motor activity would influence performance on a perceptual/cognitive task can be traced to Piaget (1952) and Piaget and Inhelder (1956), and research on MR in children and adults had already revealed that MR involving representations of hands is influenced by the posture of participants' own hands (Funk, Brugger, & Wilkening, 2005). Similarly, other research had shown that young children's MR of representations of objects is influenced by their concurrent manual activity (Frick, Daum, Walser, & Mast, 2009; Frick, Daum, Wilson, & Wilkening, 2009). In part because Campos et al. (2000) had provided convincing evidence that the onset of locomotion has dramatic effects on spatial cognition, Schwarzer, Freitag, Buckel, and Lofruthe (2013) examined the relationship between crawling experience and MR competence in 9-month-olds. Using a method similar to ours (Moore & Johnson, 2008), these researchers found that infants who had begun crawling spent more time looking at a mirror-image test object than at novel views of a habituation object, thereby providing evidence of MR; in contrast, infants of the same age who had not yet had experience crawling treated the test stimuli identically. Schwarzer and colleagues' subsequent studies successfully replicated and extended this effect (Gerhard & Schwarzer, 2018; Schwarzer, Freitag, & Schum, 2013). Note that this effect most likely depends on infants' *self-initiated* crawling rather than on increased opportunities to view objects from different perspectives, because crawling and non-crawling infants of the same age both see objects from multiple perspectives when they are carried by adults (J. Benson, personal communication, September 15, 2019).

As suggested by results mentioned previously (Frick, Daum, Walser, & Mast, 2009; Frick, Daum, Wilson, & Wilkening, 2009; Funk et al., 2005), gross motor activity such as crawling is not the only kind of motor activity that influences MR performance in infancy. In 2010, Soska, Adolph, and Johnson reported that 4.5- to 7.5-month-olds' 3D object completion was aided by experience with visually coordinated manual object exploration, which suggested to Schwarzer, Freitag, and Schum (2013) that this sort of manual experience might facilitate MR performances in infants as well. Likewise, based on earlier work with a slightly older population (Frick & Wang, 2014), Möhring and Frick (2013) hypothesized that manual experience with an object would influence 6-month-olds' subsequent MR of that object. Using a VoE method, these researchers discovered that infants given hands-on experience with an object prior to an MR test spent more time looking at a mirror-image test object than at a novel view of the previously seen object, while infants who merely *saw* the object prior to the testing sequence failed to discriminate the test objects. Schwarzer, Freitag, and Schum's (2013) study of the effects of manual object exploration on MR revealed a similar effect in non-crawling 9-month-olds, and a follow-up study by Frick and Möhring (2013) found a positive relation between parent-reported motor development in infants and their performance in the VoE MR task. Taken together, these results strongly suggest that both gross and fine motor experiences influence MR competence in the second half of the first year after birth.

To date, the only study we know of that has examined how experiences influence MR performance in younger infants is one conducted in our laboratories. Slone et al. (2018) used a "sticky mittens" procedure (Needham, Barrett, & Peterman, 2002) to give 4-month-old infants manual experience with objects prior to when they would ordinarily develop the ability to manually explore objects spontaneously. By affixing "loop" and "hook" Velcro strips to cloth mittens and small objects, respectively, and then fitting infant participants with the mittens, 4-month-olds can be enabled to "pick up" objects simply by making contact with them, even if they do not yet possess the manual dexterity that allows older infants to actually grasp objects (see Fig. 5). Following this experience, infants in an experimental group were tested using the standard method developed for the Moore and Johnson (2008) study. The results revealed a statistically significant relation between spontaneous object engagement (defined as coordinated looking and touching plus looking alone plus touching alone) and MR performance (defined as a

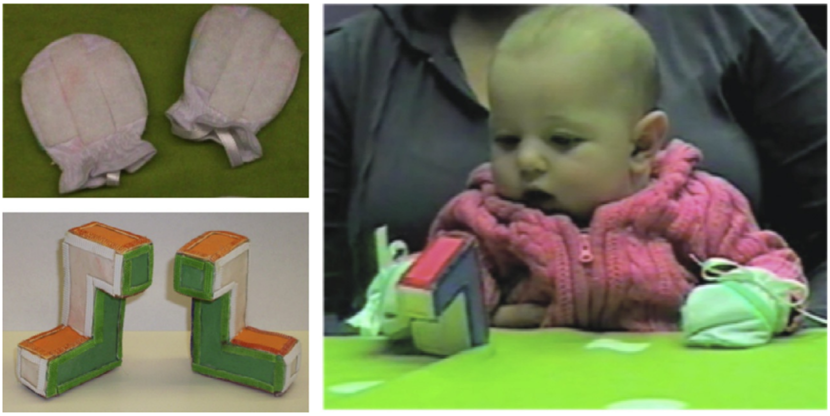

Fig. 5 Photographs illustrating the object exploration task implemented by Slone et al. (2018). Left, top: Velcro mittens worn by infants in the object exploration task. Left, bottom: The two objects presented to infants during the object exploration task. Right: An infant participating in the object exploration task. (The infant's parent provided written informed consent to publish this image.) *Reproduced from Slone, L. K., Moore, D. S., & Johnson, S. P. (2018). Object exploration facilitates 4-month-olds' mental rotation performance.* PLoS One, 13*(8), e0200468; fig. 2*.

visual preference for the mirror-image test object over a novel view of the habituation object). Specifically, infants who had "sticky mittens" experiences prior to being tested and who exhibited more engagement with the object had stronger preferences for the novel (mirror-image) object. Thus, the available evidence suggests quite strongly that motor developments—and more generally, the visual, proprioceptive, and multimodal experiences they provide (Bahrick & Lickliter, 2014)—are important contributors to the development of MR competence.

4.2 Stimulus or task complexity

Another factor that appears to influence MR competence is stimulus or task complexity. Complexity must be understood in this context as varying as a function of an infants' developmental state; a stimulus or task that is complex from one infant's perspective might be simple from the perspective of an older infant. Accordingly, the same stimulus or task that yielded novelty preferences (on average) from 5-month-old males in the Moore and Johnson (2008) study yielded familiarity preferences (on average) from 3-month-old males in the Moore and Johnson (2011) study. Consistent with Hunter and Ames' model (Hunter & Ames, 1988; Hunter et al., 1983), the younger infants' preferences for the familiar test object suggest that they had not completed processing the stimulus during the initial (i.e., habituation) phases of the experiment, presumably because it was a relatively complex stimulus from their perspective. Similarly, we observed significant familiarity preferences among 5-month-old infants when they were tested using our 2008 stimuli, but in a task involving dual computer monitors (Christodoulou et al., 2016). Although we had hypothesized that the simultaneous availability of a mirror-image test display and a non-mirror-image test display would facilitate infants' performances by reducing the demand on their short-term memory stores (Oakes & Ribar, 2005), our finding that male infants had a significant preference for the familiarized object suggested that the structure of this task actually made it *more* complex than our standard single-monitor task.

Independent evidence that familiarity preferences reflect more challenging tasks has been provided by two studies conducted in Germany. Gerhard and Schwarzer (2018) reported that among 9-month-olds who had begun crawling, a task requiring MR through a minimal angle of rotation generated the expected novelty preference. In contrast, infants in this group who were tested in a task requiring MR through a much larger angle exhibited a *familiarity* preference at test. Given the well-established finding that MR of an object through progressively larger angles takes progressively more time for adults—and that these are therefore arguably more difficult tasks—the finding that a task requiring a larger angle of rotation yielded familiarity preferences in 9-month-olds supports the claim that familiarity preferences are indicative of increased task difficulty. The only other study of MR in infants to find a familiarity preference yielded data that could be interpreted similarly (Schwarzer, Freitag, & Schum, 2013): 9-month-olds with significant motor experience (i.e., crawling infants, or non-crawling infants who displayed relatively high levels of spontaneous manual object exploration) exhibited the expected novelty preference, but non-crawling 9-month-olds who did *not* spontaneously explore objects with their hands—whose less sophisticated forms of exploration could be taken as evidence of being in an earlier developmental state—exhibited a "strong preference for the familiar object" (p. 5), consistent with the idea that a given task would be more complex for an infant in an earlier developmental state.

Thus, four studies from two independent laboratories have yielded familiarity preferences rather than novelty preferences. Although there have been varying reasons why different experimental tasks might have been more challenging for different groups of infants, in each case more complex tasks (given the participants' developmental states) have always been more likely to yield familiarity preferences. Consequently, it seems reasonable to conclude that stimulus or task complexity influences MR competence in infants much as it does in older populations (e.g., Bethell-Fox & Shepard, 1988).

4.3 Hormones

Relatively large sex differences have consistently been observed in variables such as height, sexual orientation, and gender identity, and the development of these characteristics appears to be influenced by exposure to testosterone early in life (Hines, 2015). Consequently, it is possible that a sex difference in MR, too, is affected by hormonal factors. In adult women, normal hormonal variations across the menstrual cycle are correlated with performances on MR tasks (Hausmann et al., 2000), and two double-blind placebo-controlled experiments have demonstrated that a single half-milligram dose of testosterone can temporarily improve healthy young women's performances on an MR task (Aleman et al., 2004; Pintzka, Evensmoen, Lehn, & Håberg, 2016). Thus, specific steroid hormones appear able to influence spatial ability via an *activating* role in the central nervous system.

In addition, variations in exposure to prenatal androgens such as testosterone appear to contribute to later-emerging sex differences by affecting the *organization* of the developing nervous system early in life. For example, children's gender-related playmate and toy preferences are affected by prenatal testosterone exposure (Constantinescu & Hines, 2012). The influence of prenatal and early postnatal hormones on later-appearing *cognitive* sex differences is less clear (Hines, 2010, 2015). Notwithstanding this lack of clarity, prenatal androgen exposure was correlated with speed of MR in one study of 7-year-old girls (Grimshaw et al., 1995) and some studies (Berenbaum, Korman Bryk, & Beltz, 2012; Hampson, Rovet, & Altmann, 1998; Resnick, Berenbaum, Gottesman, & Bouchard, 1986) have found that prenatal exposure to abnormally high levels of testosterone in females with congenital adrenal hyperplasia is associated with better MR performances.[b] Given these findings, some researchers have begun to explore the possibility that early-life exposure to hormones is related to infants' performances in our standard MR task. These scientists have examined both prenatal and early postnatal hormone levels, because both of these developmental periods are characterized by dramatically different concentrations of gonadal steroids in male versus female fetuses and newborns (Corbier, Edwards, & Roffi, 1992; Gendrel, Chaussain, Roger, & Job, 1980; Hammond, Koivisto, Kouvalainen, & Vihko, 1979; Lamminmäki et al., 2012; Reyes, Boroditsky, Winter, & Faiman, 1974).

A recent study examined the relation between levels of testosterone and estradiol measured in amniotic fluid surrounding 14- to 15-week-old fetuses, and the MR performances of these individuals approximately 1 year later, when they were 6-month-old babies (Erdmann et al., 2019). Although this study did not find any sex differences in behavior, MR performances of boys were nonetheless correlated with their exposure to testosterone (but not estradiol) in utero. In contrast, MR performances of girls were correlated with prenatal estradiol (but not testosterone) exposure. Replication of these intriguing and potentially important results will be necessary, of course.

Similarly, a study conducted by our collaborators in England examined the relation between MR performances in 5- to 6-month-olds and their levels of salivary testosterone measured several months earlier, when they were 1 to 2.5 months of age (Constantinescu et al., 2018). This period

[b] Note, however, that other studies of females with congenital adrenal hyperplasia have yielded results that have contradicted these findings. For example, see Helleday, Bartfai, Ritzen, and Forsman (1994), Hines et al. (2003), and Malouf, Migeon, Carson, Pertrucci, and Wisniewski (2006).

between the first and third postnatal months has been called "mini-puberty" (Lamminmäki et al., 2012) because of a surge in testosterone that is especially large in boys at this time (Corbier et al., 1992; Gendrel et al., 1980; Hammond et al., 1979). The timing of this surge is thought to be potentially important to human cognitive development (Lyall et al., 2015), because it occurs during a period of rapid cortical development, including in regions of the brain that appear to be active during MR in adults (Gogos et al., 2010; Schendan & Stern, 2007; Schöning et al., 2007). In addition to replicating the sex difference in MR performance reported by Moore and Johnson (2008), Constantinescu and colleagues found a significant positive correlation ($p = .01$) between boys' early postnatal testosterone exposure and their MR performances at 5–6 months of age. Although these results, like those of Erdmann et al. (2019), will need to be replicated, Constantinescu and colleagues concluded that hormonal events during "mini-puberty" might have lasting organizational influences on boys' central nervous systems, influences that affect their MR competence later in infancy. The mechanisms by which hormones might influence later spatial cognition remain unknown at present, although a candidate mechanism could involve hormonal modulation of gene transcription in neurons in specific brain regions (Hampson, 2018; Hara, Waters, McEwen, & Morrison, 2015).

4.4 Parental attitudes

In addition to studying hormone concentrations, Constantinescu et al. (2018) were interested in examining how social factors might relate to infants' MR performances. To this end, they provided infants' parents with a questionnaire designed to evaluate their attitudes regarding gender. The Child Gender Socialization Scale (the CGS Scale; Blakemore & Hill, 2008) was designed to assess the extent to which parents' attitudes are gender-stereotypical; it consists of 28 items that differentiate between boys' parents and girls' parents, and between parents with more versus less traditional ideas about gendered activities, such as taking ballet lessons or playing with toy cars. Somewhat surprisingly—given the very young age of the infants tested in this study—Pearson analyses revealed a significant correlation between 5-month-old girls' performances on the MR test and their parents' scores on the "Disapproval of other-gender characteristics" subscale of the CGS Scale. Specifically, parents with less traditional ideas about gendered activities—that is, parents who were more likely to say they would approve of a daughter exhibiting male-typical behaviors like playing football or playing with toy guns—were more likely to have 5-month-old daughters who provided evidence of successful MR in our standard task. Just as the correlation between early postnatal testosterone exposure and later MR was present in boys only, this correlation between parental attitudes and MR performance was present in girls only, for reasons that remain unclear at the moment. And like the finding regarding testosterone, this finding about parental attitudes will require replication.

Although we do not currently know how parental attitudes could influence infants' MR performances, existing data render it reasonable to expect social and other experiential factors to contribute to the development of MR competence, and to the development of the sex difference in this skill that emerges later in life (Halpern, 2000; Lauer et al., 2019; Levine et al., 2016). Experiences with particular stimuli and tasks are known to influence children's and adults' performances on spatial ability tests in general (Baenninger & Newcombe, 1995), and individuals who choose to participate in activities that require spatial skills have better MR abilities (Peters, Lehmann, Takahira, Takeuchi, & Jordan, 2006; Quaiser-Pohl & Lehmann, 2002; Voyer, Nolan, & Voyer, 2000). For example, experience with computers has been shown to mediate the sex difference in MR ability (Terlecki & Newcombe, 2005). Furthermore, experimental protocols designed to *train* spatial-cognitive skills improve both males' and females' performances on spatial tasks (Baenninger & Newcombe, 1989; Sanz de Acedo Lizarraga & García Ganuza, 2003).

Because male and female individuals encounter different social worlds even in early infancy (Donovan, Taylor, & Leavitt, 2007; Stern & Karraker, 1989), it is likely that the sex difference in MR competence reflects the effects of these differing experiences as well as the effects of the stereotype-based expectations to which individuals are exposed (Levine et al., 2016). In fact, women have been shown to perform less well on MR tasks when they are provided with a reminder about their gender prior to being tested (McGlone & Aronson, 2006). Similarly, when women are explicitly told that "men outperform women" on a difficult visuospatial task (Campbell & Collaer, 2009) or that "men are better" on an MR task (Heil, Jansen, Quaiser-Pohl, & Neuburger, 2012), their performances are negatively affected. Thus, experiences—including the beliefs we have about ourselves and that others have about us—can be expected to contribute to the development of MR competence, as well as to spatial-cognitive competence more generally.

5. Conclusion

Although the data collected to date suggest that MR can be detected as early as 3 months of age, we remain largely ignorant about the mechanisms by which this ability develops. Clearly, important developmental events are occurring either prenatally or in the first 3 months of postnatal life. Further research on the role of genetic, hormonal, and experiential factors in the development of MR competence will be required to illuminate these developmental processes. Likewise, we remain unsure if the sex difference in MR that is detectable in older populations is present in infants, and if so, what the underlying causes of this difference might be. Most gender differences in human behavior result from numerous factors interacting over time (Moore, 2012), and the factors that contribute to differences in MR competence are likely those that contribute to gender differences more broadly, including early exposure to steroid hormones like testosterone and socialization by parents, siblings, and teachers, as well as self-socialization based on an individual's understanding of gender (Halpern, 2000; Hines, 2015). The interactions that drive development of MR competence early in life are likely to be complex, but research that elucidates these processes can be expected to have significant payoffs, because understanding the development of this important skill will facilitate the creation of interventions that can improve performances and open doors to productive careers.

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