

Mental representations of rotation in young children

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Table of Contents

Zusammenfassung	4
Abstract	5
List of Studies.....	6
Synopsis	7
General introduction	8
Overview of Study 1	14
Overview of Study 2.....	17
Overview of Study 3.....	19
General discussion.....	20
Conclusion	25
References	27
Study 1.....	34
Study 2.....	80
Study 3.....	122
Acknowledgments	149

Zusammenfassung

In der vorliegenden These wurde untersucht, wie sich mentale Repräsentationen von Drehbewegungen entwickeln im Alter zwischen 2 und 5.5 Jahren. In Studie 1 wurde Kleinkindern eine Form gezeigt, die sich drehte, kurz hinter einem Okkluder verschwand und dann wiedererschien, entweder in der originalen oder spiegelverkehrten Version. Eye-Tracking-Resultate zeigten, dass die Kleinkinder zwischen 2 und 3 Jahren während der sichtbaren Rotation das Schauen auf den äusseren Teil der rotierenden Form vermehrt kombinierten mit Blicken zum Drehpunkt. Dies könnte bedeuten, dass die Kinder verstärkt enkodierten, wie sich die Orientierung der rotierenden Form änderte. Als die Form kurz hinter dem Okkluder verschwand, zeigten die Kleinkinder auch zunehmend prädiktive Augenbewegungen zur Wiedererscheinenseite des Okkluders. Allerdings ist nicht klar, ob sie bemerkten, dass die Form, die wiedererschien, manchmal spiegelverkehrt war. In einem Object-Fitting-Task drehten die Kinder immer öfters Holzklötze schon im Vornherein, bevor sie versuchten, diese durch eine Öffnung in eine Box zu bringen. Studie 2 zeigte, dass sich Augenbewegungen während dem Beobachten von sichtbarer Rotation weiterhin entwickeln im Alter zwischen 3.5 und 5.5 Jahren. Zudem konnten Kinder in einer neuen Aufgabe zur mentalen Rotation bereits im Alter zwischen 3.5 und 4 Jahren asymmetrische Formen mental rotieren und diese von spiegelverkehrten Versionen unterscheiden. Studie 3 zeigte, dass sogar Kinder im Alter zwischen 3 und 3.5 Jahren diese neue Aufgabe zur mentalen Rotation überzufällig lösen konnten. Zusammengekommen lässt sich konkludieren, dass sich das Wahrnehmen von Rotationsbewegungen und das Denken darüber stark entwickeln im Alter zwischen 2 und 5.5 Jahren.

Abstract

The present thesis investigated how mental representations of rotation develop between 2 and 5.5 years of age. In Study 1, toddlers were presented with a rotating shape that disappeared briefly behind an occluder and reappeared either in its original or mirror-reversed form. Eye-tracking results showed that during visible rotation, toddlers between 2 and 3 years of age increasingly combined looking at the outer part of the rotating shape with looks to the pivot point. Thus, they may have increasingly encoded how the orientation of the rotating shape changed. When the shape disappeared briefly behind an occluder, the toddlers also increasingly showed predictive eye-movements to the reappearance side of the occluder. However, it is unclear whether they noticed that the shape that reappeared was sometimes mirror-reversed. In an object-fitting task, toddlers increasingly rotated wooden blocks prospectively before they tried to insert them through apertures into a box. Study 2 showed that eye movements during visible rotation continued to develop between 3.5 and 5.5 years of age. Moreover, in a novel mental-rotation task, children between 3.5 and 4 years of age could mentally rotate asymmetrical shapes and distinguish them from mirror images. Study 3 showed that even children between 3 and 3.5 years of age could solve the novel mental-rotation task above chance. Taken together, it can be concluded that perceiving and thinking about rotation develop markedly between 2 and 5.5 years of age.

List of Studies

Study 1

Pedrett, S., Kaspar, L. & Frick, A. (in press). Understanding of object rotation between two and three years of age. *Developmental Psychology*.

Study 2

Pedrett, S., Chavaillaz, A. & Frick, A. (submitted). Age-related changes in how 3.5- to 5.5-year-olds observe and imagine rotational object motion.

Study 3

Pedrett, S. & Frick, A. (ready to submit). Children between 3 and 3.5 years of age can perform mental rotation of asymmetrical shapes.

Synopsis

General introduction

In the first years of life, children have the challenge to figure out how to perceive and understand a world that is full of motion. A basic type of motion is rotation, which is the focus of the present thesis. How do children learn to perceive objects that rotate? How do they learn to understand this type of motion, and at which age can children even imagine rotation? The aim of the present thesis was to systematically unriddle these questions by measuring eye movements, actions, and conscious responses in young children.

Perception and mental representations of translational motion

Previous studies have already investigated how infants encode translational motion, such as vertical or horizontal motion. It was found that during the first months of life, infants learn to follow objects with their eyes. This tracking is rather jerky in the first 2 months, but gets smoother with age (e.g., Jacobs, Harris, Shawkat & Taylor, 1997; Phillips, Finocchio, Ong & Fuchs, 1997; Pieh, Proudlock & Gottlob, 2011; Rosander & von Hofsten, 2002; Rüttsche, Baumann, Jiang & Mojon, 2006). Tracking an upright object that moves on a circular trajectory is more difficult for infants (Grönqvist, Gredebäck & von Hofsten, 2006) but also develops dramatically during infancy (Gredebäck, von Hofsten, Karlsson & Aus, 2005). With age, infants increasingly mentally represent and predict future motion, so that when they track a moving object, gaze lags less behind the moving object (e.g., Gredebäck et al., 2005). Moreover, within the first year of life, infants start to form mental representations of hidden motion, so that when a moving object disappears behind an occluder, they look predictively to the reappearance side of the occluder (e.g., Bertenthal, Gredebäck & Boyer, 2012; Johnson & Shuwairi, 2009; von Hofsten, Kochukhova & Rosander, 2007; Woods, Wilcox, Armstrong & Alexander, 2010). This was also found for circular motion (Gredebäck & Hofsten, 2004; Gredebäck, von Hofsten & Boudreau, 2002). In adults, even *smooth* mental representations of motion have been found: If the room is dark and the moving object blanks

out briefly, adults sometimes follow the invisible object with smooth pursuit eye movements (e.g., Bennett & Barnes, 2003, 2004). Research on representational momentum demonstrated that when a moving object disappears abruptly, adults report the object's last position slightly further ahead from where it had actually vanished (e.g., Hubbard, 2005). This shows that adults automatically extrapolate motion somewhat. Representational momentum covers a smaller distance than predictive eye-movements over a large occluder, however, and might thus be based on different cognitive processes.

Mental representations of rotational motion

Regarding mental representations of rotation, it has been proposed that infants (Hespos & Rochat, 1997; Rochat & Hespos, 1996) and 16-month-old toddlers (Frick & Wang, 2014) understand how the orientation of an object should change during a hidden rotation; participants looked longer at a scene if the object reappeared in a wrong rather than the correct orientation. At 14 months of age, toddlers often also understand that a cylindrical wooden block needs to be rotated into a vertical orientation in order to fit through a circular aperture into a box. Toddlers at this age often rotate such a wooden block prospectively before they try to fit it through an aperture (Örnkloo & von Hofsten, 2007). In the following months, these preadjustments improve (Örnkloo & von Hofsten, 2007). At 24 months of age, children preadjust objects such as rectangular blocks to fit them into rectangular apertures (Smith, Street, Jones & James, 2014). Similarly, toddlers at 24 months of age also orient a disk correctly before they try to fit it through a slot (Street, James, Jones & Smith, 2011). At 26 months of age, toddlers also prospectively rotate more complicated shapes, such as isosceles triangles, to fit them into corresponding apertures (Örnkloo & von Hofsten, 2007). Studies with motion-tracking technology found that prospective alignment improves rather continuously between approximately 1.5 to 3 years of age (Jung, Kahrs & Lockman, 2015, 2018), see Lockman, Fears and Jung (2018) for a review. Taken together, these object-fitting

studies demonstrated that prospective rotation of the longitudinal axis increases between 14 and 36 months of age, and that with increasing age, toddlers also increasingly consider additional features. What is not clear from these results, however, is whether toddlers imagined rotation, or whether they adjusted the objects iteratively in the air, compared the orientation with the aperture, and repeated these steps until the objects were preadjusted correctly.

Tasks that measure mental rotation more directly focus on highly asymmetrical shapes, such as a 'p' or 'q', and require participants to mentally rotate them so detailed that they can distinguish the mentally rotated object from its mirror image. Typically, participants are asked to compare objects that differ in orientation and to decide whether the objects are the same or mirror versions of each other (e.g., Cooper, 1975; Shepard & Metzler, 1971; Vandenberg & Kuse, 1978; Vingerhoets, de Lange, Vandemaele, Deblaere & Achten, 2002; Wexler, Kosslyn & Berthoz, 1998). These tasks do not test for simpler types of mental rotation, such as imagery of how a line would be oriented after rotation, or how a 'T' would look like after rotation. Imagining the rotation of a simple line requires only to imagine how the orientation of the line changes. Imagining the rotation of a 'T' in addition also requires to imagine the position and orientation of the top bar. Thus, the internal configurations of the object stay the same throughout the rotation. For mental rotation of an asymmetrical shape like a 'p', participants need to consider also in which direction the round part of the shape would face after the rotation, relatively to the shape's stem. Thus, there are more internal configurations that stay stable throughout the rotation. For this reason, mental-rotation tasks, which use highly asymmetrical shapes, probably tap already a very sophisticated type of mental rotation.

The very nature of mental rotation is part of the imagery debate. It has been argued that mental rotation is kinetic imagery and that during mental-rotation tasks, participants

mentally rotate the object in a smooth manner, going through all intermediate orientations (e.g., Attneave, 1974). However, it has also been argued that participants use piecemeal rotation or no imagery of rotation at all (Pylyshyn, 1979). The idea of no kinetic imagery is not as impossible as it may sound. This can be explained using horizontal motion as example. In order to get the knowledge of where a moving object will be, say, in 10 seconds, one could imagine each intermediate step in a continuous manner. Given velocity, one could also compute more mathematically where the object will be in 10 seconds. Similarly, a computer can actually rotate a picture without going through all intermediate positions; instead, the computer can use mathematical rules to compute the new picture directly. If a computer can do that, we can do that maybe too. A possible non-kinetic strategy can be illustrated using a task as example, in which the participant is presented with an upright 'p' and a rotated shape that could be either a 'p' or 'q'. The task is to decide whether the second shape is the same as the upright 'p'. To solve this task, the participant can use a polar coordinate system in which directions can be described with words such as "clockwise" or "counter-clockwise". First, the participant can look at the upright 'p' and notice that the round part of the 'p' faces in the clockwise direction. Then, the participant can look at the rotated shape and check whether the round part does also face in the clockwise direction. If yes, the shape is a 'p', otherwise, it is a 'q'. To solve this task, it is hence not necessary to mentally rotate the whole 'p' by going through all intermediate orientations, but the participant could use a polar coordinate system to describe the internal configurations of the object. In the present thesis, the term *mental rotation* refers not only to kinetic imagery of rotation, but also to possible non-kinetic cognitive processes if they result in an accurate knowledge of what an object would look like in another orientation. Thus, success in a mental-rotation task, I consider mental rotation regardless of whether a kinetic or non-kinetic strategy was used.

Development of mental rotation of highly asymmetrical shapes has been investigated many times. When presented with 3D-objects made of wooden cubes, children started to have success between 5-8 years of age (Hawes, LeFevre, Xu & Bruce, 2015). Already at 5-6 years of age, though, children could mentally rotate 3D-airplanes (Foulkes & Hollifield, 1989). Children at 5-6 years of age could also determine whether a car that was depicted in a unusual orientation would drive to the left or to the right if it were upright (Funk, Brugger & Wilkening, 2005). When asked to decide whether two bears that differed in orientation were the same or different, 5-year-olds could mentally rotate up to 150° (Marmor, 1975). Further studies confirmed mental rotation of various 2D-objects in 5-year-olds (Frick, Daum, Walser & Mast, 2009; Frick, Ferrara & Newcombe, 2013; Hahn, Jansen & Heil, 2010a, 2010b; Kosslyn, Margolis, Barrett, Goldknopf & Daly, 1990; Krüger & Krist, 2009; Quaiser-Pohl, Rohe & Amberger, 2010). However, studies in which success rates were lower (Dean & Harvey, 1979; Platt & Cohen, 1981) show that mental rotation in 5-year-olds is not yet stable. In 4-year-old children (4 years 0 months to 4 years 11 months), mental rotation of up to 150° was found in a study that offered thorough training with two upright stimuli (Marmor, 1977). In a task with ghosts as stimuli, 4-year-olds showed mental rotation of up to 120° (Frick, Hansen & Newcombe, 2013). In their task, children were presented with two ghosts that were mirror images of each other. The children were asked to select the ghost that would fit into a hole. This task thus used a nonverbal answer format, which might be a reason for the success of 4-year-olds. In two other studies, in which children had to decide whether two shapes were the same or different, 4-year-old children had success in approximately 60-70% of the trials, mostly if the shapes did not differ much in orientation (Estes, 1998; Wimmer, Maras, Robinson & Thomas, 2016). Below 4 years of age, no clear evidence for mental rotation was found (Frick, Ferrara & Newcombe, 2013; Frick, Hansen & Newcombe, 2013; Noda, 2010), but mental rotation of ghosts (Fernández-Méndez, Contreras & Elosúa, 2018) or other

pictures (Krüger & Krist, 2009) may be trained over several training sessions. It is not known whether 3-year-olds struggle in mental-rotation tasks because of mental rotation or because of other task demands such as understanding instructions and decision making. Some first evidence might point to mental rotation of a highly asymmetrical shape at an earlier age. Infants were presented with a 'p' or 'q' that disappeared behind an occluder and then reappeared either correctly or as the mirror version, in an orientation ranging from 0 to 180° (Frick & Möhring, 2013; Möhring & Frick, 2013). Infants looked longer if the mirror version rather the correct shape reappeared. This could mean that infants can already mentally rotate asymmetrical shapes and distinguish them from mirror images.

In summary, the previous studies indicated that children start to have success in mental-rotation tasks with highly asymmetrical shapes between approximately 4 and 6 years of age and thus show mental rotation on a high level of sophistication. Toddlers below 3 years of age prospectively rotate shapes such as triangles or rectangles in object-fitting tasks, but it is unclear whether a simple type of mental rotation or other cognitive processes are behind these preadjustments. Maybe, infants can imagine rotation somewhat. Taken together, it is unclear what exactly happens before 4 years of age. Moreover, little is known about how children encode visible rotation.

Aim of the present thesis

The aim of the present thesis was hence to discover how mental rotation or possible precursors develop in 2- to 5-year-old children. In Study 1, we investigated this in toddlers between 2 and 3 years of age, using a multi-method approach consisting of measuring eye movements, looking times, and object-fitting (Pedrett, Kaspar & Frick, in press). In Study 2, we investigated whether children just below 4 years of age can solve a novel mental-rotation task if task requirements that are irrelevant for mental rotation are lowered, and whether a looking-time task can detect mental rotation nevertheless more sensitively. We also tested

how mental rotation and perception of rotation develop further until 5.5 years of age (Pedrett, Chavaillaz & Frick, in preparation). In Study 3, we investigated whether mental rotation can be discovered even between 3 and 3.5 years of age with the novel mental-rotation task, with instructions that were further adapted to young children (Pedrett & Frick, in preparation).

Overview of Study 1

The previous object-fitting tasks showed that toddlers rotate objects prospectively before fitting them into apertures (Jung et al., 2015, 2018; Örnkloo & von Hofsten, 2007; Smith et al., 2014; Street et al., 2011), but the cognitive processes behind these actions are unknown. Generally, little is known about toddlers' perception and mental representations of rotation. Therefore, the goal of Study 1 (Pedrett et al., in press) was to systematically investigate how perception of rotation, mental representations of rotation, and actions develop during toddlerhood. Do these areas develop during the same time period and possibly even correlate, or do they develop after each other? These questions were tested in a study with 44 toddlers between age 1;10 and 3;2 (years;months). Each toddler participated in an eye-tracking task and in an object-fitting task.

In the eye-tracking task, toddlers were presented with computer animations of an object that looked like the letter 'p'. The object rotated clockwise around its foot, disappeared behind an occluder that looked like a piece of pie, and then reappeared at the other side of the occluder, either correctly or mirror-reversed (like a 'q').

Eye movements during visible rotation before the occlusion revealed that the toddlers mostly followed the outer part of the rotating stimulus. With increasing age, though, the toddlers increasingly combined this with saccades to the pivot point. Thus, with increasing age, toddlers did not only track motion, but increasingly disengaged from following the motion and instead made gaze shifts to the pivot point. It may be concluded that tracking mostly the outer part of the rotating shape would have provided the toddlers especially with

the information of how the outer part of the shape moved along a circular trajectory. In contrast, looking not only at the outer part of the rotating shape but also making gaze shifts to the pivot point probably let the toddlers encode how the *orientation* of the shape changed, which is a hallmark of the motion type *rotation*. Thus, with increasing age, the toddlers probably paid increasing attention to features that were specific for rotary movement.

When the shape had disappeared behind the occluder, results showed that with increasing age, toddlers' gaze arrived earlier, more predictively, at the reappearance side of the occluder. We concluded that with increasing age, toddlers formed a stronger expectation of where the object would reappear. Results also showed that with increasing age, the toddlers looked less often back to the disappearance side of the occluder. This demonstrated that the age effect on predictive eye-movements to the reappearance side of the occluder was not just an age effect on speed, but that with increasing age, toddlers were more convinced that the shape would reappear at the reappearance rather than the disappearance side of the occluder. However, the nature of this mental representation is not entirely clear. Toddlers could have imagined rotation (i.e., how the orientation of the longitudinal axis of the shape changed), or they could have imagined just the circular trajectory of the outer part of the rotating shape. Thus, it is an open question whether toddlers' predictive eye-movements were specific to mental representations of the motion type *rotation*.

Whether the toddlers mentally rotated the object so detailed that they could distinguish it from a mirror image was tested by measuring toddlers' looking times after the occlusion. We had hypothesized that if toddlers mentally rotated the object on this level of sophistication, they would know what the shape would look like after the occlusion and be surprised when the mirror-reversed shape reappeared. This violation of expectation would cause prolonged looking times, as compared to the condition in which the original shape reappeared. Contrary to our hypothesis, however, toddlers' looking times did not differ

between conditions in which the original versus the mirror-reversed shape reappeared. Thus, we could not find the looking-time effects found in infant studies (Frick & Möhring, 2013; Möhring & Frick, 2013) in the present study with 2- to 3-year-olds. Toddlers' looking times did not yield evidence for mental rotation. However, our results could also not disprove mental rotation on this level of sophistication, as looking times are an indirect measure and it is hence possible that toddlers noticed whether the mirror or original shape reappeared, but that this did not reflect in their looking times.

In the object-fitting task, toddlers inserted elongated wooden blocks through apertures into a box. The results showed that with increasing age, the toddlers preadjusted the wooden blocks more frequently and had also more success at actually inserting the wooden blocks. Thus, this study could replicate previous findings (Örnkloo & von Hofsten, 2007) and show again that toddlers' actions indicate that understanding of rotation develops during toddlerhood.

We also analyzed correlations between measures. In the eye-tracking task, we found a correlation between toddlers' eye movements during visible rotation and their anticipatory looks to the reappearance side of the occluder. The more the toddlers shifted their gaze between the outer part of the stimulus and the pivot point during visible rotation, the earlier their gaze arrived at the reappearance side of the occluder. This showed that encoding of visible rotation is linked to mental representations. We discussed that maybe, gaze shifts between the outer part of the rotating stimulus and the pivot point during visible rotation had provided toddlers with information of how the orientation of the shape changed, and that this led to predictive eye-movements to the reappearance side of the occluder. Another explanation for the correlation, however, could be that some toddlers generally looked around more with saccades than other toddlers.

Correlational analyses also revealed that predictive eye-movements in the eye-tracking task correlated with preadjustments in the object-fitting task (even if controlled for age and visual attention in the eye-tracking task). The earlier toddlers' gaze arrived at the reappearance side of the occluder in the eye-tracking task, the more frequently toddlers preadjusted wooden blocks. A common underlying cognitive process for both anticipatory eye-movements to the reappearance side of the occluder and preadjustments of wooden blocks might be that toddlers imagined rotation on a simple level of sophistication.

In summary, Study 1 showed that during toddlerhood, development happens in how toddlers encode visible rotation, in predictive eye-movements, as well in preadjustment and success in an object-fitting task. Thus, this study showed that toddlerhood is a time when all these areas develop in parallel, and that some of these areas even correlate. However, Study 1 did not provide evidence for mental rotation on a level of sophistication that would allow to distinguish between mirror images of asymmetrical shapes.

Overview of Study 2

Previous research, taken together, showed that 4 to almost 6 years is approximately the age when children start to have success in behavioral mental-rotation tasks (e.g., Estes, 1998; Frick, Ferrara & Newcombe, 2013; Frick, Hansen & Newcombe, 2013; Marmor, 1977; Quaiser-Pohl et al., 2010). With training, success was possible a few months earlier (Fernández-Méndez et al., 2018; Krüger, 2018). However, a previous object-fitting study showed that 26-month-olds prospectively align shapes such as rectangles and triangles (Örnkloo & von Hofsten, 2007), and Study 1 also showed that between 2 and 3 years of age, toddlers increasingly prealign shapes such as half-circles. We wondered therefore what happens between these sophisticated preadjustments at 36 months of age and eventual success in mental-rotation tasks at approximately 4 to 6 years of age. What if we created a simpler mental-rotation task by removing task requirements that are irrelevant for mental

rotation? Can children around the fourth birthday, or even younger children, already solve this task and thus show mental rotation of highly asymmetrical shapes? Another research question was also how success in such a behavioral task relates to the implicit measure of looking time. Are implicit abilities more developed than explicit abilities (Frick, Möhring & Newcombe, 2014) at this age? Moreover, we tested whether perception of rotation and anticipatory eye-movements develop further after 3 years of age. Participants in Study 2 (Pedrett et al., in preparation) were 74 children between 3.5 and 5.5 years of age. Each child participated in an eye-tracking task and a novel mental-rotation task.

The eye-tracking task was like the eye-tracking task in Study 1, but with small changes, such as measuring looking times automatically with the eye-tracker instead of coding them manually. Children were presented with a flag that rotated, disappeared behind an occluder, and reappeared at the other side of the occluder, either as the original shape or mirror-reversed. Results showed that during the visible rotation, children looked less at the outer part of the stimulus and switched more often towards the pivot point with increasing age. Thus, a similar age-related development in perception was found as in Study 1. During the occlusion, already the youngest children looked predictively to the reappearance side of the occluder, and no further age-related progression was found. To test whether children mentally rotated the shape so well during occlusion that they expected exactly how the shape would look after occlusion, looking-times were analyzed. Looking-time results showed that children looked roughly equally long at the screen when the shape that reappeared was the original and when it was mirror-reversed. It is thus unclear whether during occlusion, children had performed mental rotation on this level of sophistication.

In the novel mental-rotation task, children were presented with two wooden boards. On each board, a silhouette was visualized. The silhouettes were the same on both boards. Each board also had a vertical rod in the center, to which a cardboard flag could be attached

by a wire loop that was on the flag's lower end. To one board, the experimenter attached a cardboard flag that was the same as the silhouette, so that the flag could be rotated exactly onto the silhouette. Onto the other board, the experimenter attached a mirror-reversed flag, which could not be rotated exactly onto the silhouette. At the beginning of a trial, the flags differed by 90, 120, 150, or 180° from the silhouettes. The children were asked to physically rotate the flag that would fit exactly onto the silhouette. The rationale was that by means of mental rotation, children could know prospectively which flag would fit onto the silhouette and thus choose the correct one. A trial was coded as successful if the child selected the correct flag. This novel task differed from previous tasks (e.g., Frick, Hansen & Newcombe, 2013; Quaiser-Pohl et al., 2010) insofar as that to mentally superimpose one flag onto the silhouette, no imagery of vertical or horizontal motion was necessary; mental rotation alone sufficed. The pivot point and rotation direction were predefined, so that the trajectory and the task mechanics were clear, reducing the number of decisions that children needed to make. Therefore, we expected this task to be sensitive to detect mental rotation in young children. The results revealed that children between 4 and 5.5 years of age could mentally rotate up to 180°. Impressively, children between 3.5 and 4 years of age could still mentally rotate up to 150°. Thus, these children demonstrated that mental rotation of highly asymmetrical shapes is possible below 4 years of age.

Overview of Study 3

Since children between 3.5 and 4 years of age showed mental rotation in Study 2 in the novel mental-rotation task, we were encouraged to test whether even children between 3 and 3.5 years of age can solve this task. To make it more likely that so young children understand the task, we adapted the instructions to this age group. Specifically, we demonstrated more thoroughly how the task can be solved, before we asked the children to try. Moreover, we tested smaller angles (30-120°).

Participants in Study 3 (Pedrett & Frick, in preparation) were 30 children between 3 and 3.5 years of age. The results showed that although for many children, the task was hard to understand, the children chose the correct flag more often than predicted by chance. They showed mental rotation of up to 120° . This study could hence show that mental rotation is even possible between 3 and 3.5 years of age.

Some children, who had at least 12 out of 16 trials correct, participated also in an additional block in which mental rotation of 150° and 180° was tested. Some of these children had even high success rates at these difficulty levels. This shows that a few children between 3 and 3.5 years of age can mentally rotate up to 150° or 180° .

This demonstrated that mental rotation is possible between 3 and 3.5 years of age. In the discussion, we asked whether even 2-year-olds could solve a mental-rotation task with highly asymmetrical shapes if task demands on understanding instructions, control of attention, and decision making were lowered even more.

General discussion

In summary, results revealed dramatic age-related changes in mental representations of rotation. Eye-tracking results showed that children between 2 and 5.5 years of age increasingly combined tracking the outer part of a visibly rotating shape with also looking at the pivot point, suggesting that children increasingly encoded how the orientation of the shape changed, rather than only how the outer part of the shape moved on a circular trajectory (Studies 1 and 2). When the rotating shape disappeared briefly behind an occluder, children between 2 and 3 years of age increasingly looked predictively to the reappearance side of the occluder (Study 1). Within the same time period (2-3 years of age), toddlers also increasingly aligned wooden blocks prospectively before trying to insert them into apertures, with the result that at 3 years of age, they could preadjust shapes such as half-circles (Study 1). Between 3 and 3.5 years of age, children demonstrated mental rotation of highly

asymmetrical shapes and could distinguish them from mirror images (Study 3). This improved between 3.5 and 5.5 years of age (Study 2).

Perception of rotation

Children between 2 and 5.5 years of age increasingly combined tracking the outer part of the visibly rotating shape with saccades to the pivot point, so that they probably encoded specifically how the orientation of the rotating shape changed (Studies 1 and 2). This eye-movement pattern was rather complex. Sometimes, it happened that children made a gaze switch from the outer part of the shape to the pivot point and then again looked back to the outer part of the rotating shape, tracking it with smooth pursuit eye movements. This pattern was often amazingly fast and shows advanced control over different kinds of eye movements. The age-related change in how children observed the visible rotation fits well to eye movements during free scene exploration. It has been found that between 2 and 10 years of age, children look more around the older they are when they watch naturalistic images (Helo, Pannasch, Sirri & Rämä, 2014). Thus, with increasing age, children not only observe more different features of rotation, but also explore completely different kinds of scenes more. This illustrates that during childhood, it changes how children perceive the world.

Mental rotation on different levels of sophistication

Thinking about rotation also changed with increasing age. Study 1 showed that between 2 and 3 years of age, toddlers increasingly showed predictive eye-movements to the reappearance side of the occluder and also preadjusted wooden blocks more frequently. Both could be based on precursors of mental rotation. For example, predictive eye-movements could be based on mental representations of the circular trajectory of the outer part of the rotating shape, and preadjustments could be achieved by iteratively rotating the object in the air until it was prealigned. However, it is also possible that a simple type of mental rotation guided both predictive eye-movements over the occluder and preadjustments in the object-

fitting task. During the occlusion in the eye-tracking task, children might have imagined how the orientation of the shape would change, and during preadjustment of a half-circle (for example), they might have imagined how the half-circle would be oriented after rotation and in which direction the round part would face.

Study 3 showed that between 3 and 3.5 years of age, children could mentally rotate asymmetrical shapes, at least up to 120° . They could do that so well that they could distinguish them from their mirror images. Study 2 showed that between 3.5 and 4 years of age, children could mentally rotate up to 150° , and that between 4 and 5.5 years of age, mental rotation of up to 180° was possible. In this task, the shapes could be superimposed by rotational motion alone, so that no vertical or horizontal motion was necessary. In contrast, several other studies showed the shapes not only in different orientations, but also in different locations, so that additional horizontal or vertical motion was needed to superimpose them (e.g., Estes, 1998; Frick, Ferrara & Newcombe, 2013; Frick, Hansen & Newcombe, 2013; Hahn et al., 2010b; Kosslyn et al., 1990; Krüger & Krist, 2009; Marmor, 1977; Quaiser-Pohl et al., 2010; Wimmer et al., 2016). In these studies, children started to have success approximately between 4 and 6 years of age. Thus, these tasks might have tapped more advanced imagery than the novel behavioral task in Studies 2 and 3. If more complicated stimuli are used, such as abstract 3D-objects, children start to perform above chance at even later ages, approximately between 5 to 8 years of age (Hawes et al., 2015). Taken together, it seems that although some mental rotation of asymmetrical shapes is possible between 3 and 3.5 years of age, it gets much more sophisticated in the following years.

Since children between 3 and 3.5 years of age could mentally rotate highly asymmetrical shapes in Study 3, it is likely that younger children, such as the 3-year-olds in Study 1, can mentally rotate simpler shapes. It is therefore probable that the 3-year-olds in Study 1 used a simple type of mental rotation when they preadjusted shapes such as half-

circles in the object-fitting task. Similarly, it is probable that mental rotation was involved when also younger toddlers preadjusted objects (Jung et al., 2015, 2018; Örnkloo & von Hofsten, 2007; Smith et al., 2014; Street et al., 2011). For example, mental rotation in the sense of imagining how the orientation of a line would change during rotation was possibly involved when toddlers below 2 years of age raised elongated wooden blocks before trying to insert them through apertures (Örnkloo & von Hofsten, 2007).

Taking these previous studies and the present thesis together, I conclude that mental rotation of highly asymmetrical shapes exists between 3 and 3.5 years of age and develops drastically in the following years. The finding of mental rotation between 3 and 3.5 years of age adds evidence to the notion that simpler types of mental rotation such as mentally rotating a half-circle or line might exist earlier in life. This could be the reason for why toddlers preadjusted objects in object-fitting tasks and why they showed predictive eye-movements.

Automatic versus intentional mental rotation

In addition, there might be a dissociation between automatic and deliberately initiated mental rotation. It has been proposed that presentation of visible rotation could facilitate mental rotation, as motion could be just extrapolated (Frick et al., 2014). Furthermore, for adults, same-different tasks often feel difficult, whereas in daily life, adults can effortlessly preadjust a knife to cut a piece of bread, or prospectively rotate a hairbrush to brush their own or another person's hair. Viewed from the side, a hairbrush or a knife look as asymmetrical as a 'p'. Thus, prospectively rotating a hairbrush so that the actual brush and not its back side touches another person's hair could require mental rotation on the same level of sophistication as mentally rotating a 'p' so well that one could distinguish it from a 'q'. These preadjustments do not directly prove mental rotation, but if mental rotation is behind these

preadjustments, this would mean that there exists an automatic version of mental rotation that feels much easier than solving a same-different mental-rotation task.

In adults, evidence for some sort of automatic mental rotation has been found in research on representational momentum, showing that adults automatically extrapolated rotation slightly if a rotating object suddenly vanished (Freyd & Finke, 1984; Munger, Solberg & Horrocks, 1999). This extrapolation was small and far away from mental rotation of 90 or even 180°, but it was related to performance in a mental-rotation task (Munger et al., 1999).

In the present thesis, no direct evidence was found for automatic mental rotation of highly asymmetrical shapes, but maybe for automatic mental rotation on a simpler level of sophistication. Eye-tracking results showed that toddlers as young as 2 years of age looked predictively to the reappearance side of the occluder (Study 1). As mentioned above, one possible explanation is that they extrapolated the circular movement of the outer part of the rotating shape. However, it is also possible that they mentally rotated the longitudinally axis of the shape during the occlusion, so that they expected how its orientation would change, and that they therefore looked predictively to the reappearance side of the occluder. Predictive eye-movements over an occluder emerge in infancy, at least for translational motion (e.g., Bertenthal et al., 2012; Gredebäck & Hofsten, 2004; Gredebäck et al., 2002; Johnson & Shuwairi, 2009; von Hofsten et al., 2007). Therefore, the predictive eye-movements in Studies 1 and 2 may have been based on mental representations of rotation that were automatic.

Open questions and limitations

Taken together, there are at least four open questions regarding mental rotation in 2- to 5.5-year-olds. The first question is whether toddlers below 3 years of age can perform mental rotation on a simple level of sophistication, such as imagining how the orientation of a

line changes during rotation. Clues supporting this notion come from looking-times (Frick & Wang, 2014), from predictive eye-movements over the occluder in Study 1, and from preadjustments of objects in Study 1 and previous studies (Jung et al., 2015, 2018; Örnkloo & von Hofsten, 2007; Smith et al., 2014; Street et al., 2011). And since Study 3 showed mental rotation of highly asymmetrical shapes between 3 and 3.5 years of age, it is likely that children below 3 years of age can mentally rotate simpler shapes. However, this is no direct proof. The second open question is whether toddlers and preschoolers can mentally rotate *automatically*, on the same level of sophistication as mentally rotating a 'p' and distinguishing it from its mirror image. The third open question is what constitutes the limiting factor for success in the novel behavioral mental-rotation task from Study 3 in which children between 3 and 3.5 years of age performed above chance and thus showed mental rotation. Can toddlers just below 3 years of age show mental rotation of highly asymmetrical shapes such as a 'p' if task demands such as understanding instructions and decision making are further lowered? The fourth question is whether mental rotation of highly asymmetrical shapes that was found in children between 3 and 5.5 years of age (Studies 2 and 3) as well as in the previous studies on mental rotation in children (e.g., Estes, 1998; Frick, Hansen & Newcombe, 2013; Funk et al., 2005; Marmor, 1977; Quaiser-Pohl et al., 2010; Wimmer et al., 2016) is a form of kinetic imagery, or whether children use non-kinetic strategies to solve these mental-rotation tasks. Combining kinetic and non-kinetic strategies is also a possibility.

Conclusion

In conclusion, the present thesis showed that mental rotation of highly asymmetrical shapes is possible between 3 and 3.5 years of age and develops further between 3.5 and 5.5 years of age. Between 2 and 3 years of age, toddlers showed predictive eye-movements and preadjustments of wooden blocks, which may indicate a simple type of mental rotation but could also be based on other cognitive processes. Perception of visible rotation changed

between 2 and 5.5 years of age. With increasing age, children combined tracking the outer point of the rotating shape more with also attending the pivot point, so that they probably encoded more intensely how the *orientation* of the shape changed rather than just how the outer part of the shape moved on a circular trajectory. All three studies together demonstrated dramatic development of mental representations of rotation between 2 and 5.5 years of age, with developmental changes not only in thinking about rotation, but also perception.

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Study 1

Understanding of Object Rotation Between Two and Three Years of Age

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Abstract

Toddlers' understanding of object rotation was investigated using a multi-method approach. Participants were 44 toddlers between 22 and 38 months of age. In an eye-tracking task, they observed a shape that rotated and disappeared briefly behind an occluder. In an object-fitting task, they rotated wooden blocks and fit them through apertures. Results of the eye-tracking task showed that with increasing age, the toddlers encoded the visible rotation using a more complex eye-movement pattern, increasingly combining tracking movements with gaze shifts to the pivot point. During occlusion, anticipatory looks to the location where the shape would reappear increased with age, whereas looking back to the location where the shape had just disappeared decreased. This suggests that, with increasing age, the toddlers formed a clearer mental representation about the object and its rotational movement. In the object-fitting task, the toddlers succeeded more with increasing age, and also rotated the wooden blocks more often correctly before they tried to insert them. Importantly, these preadjustments correlated with anticipatory eye movements, suggesting that both measures tap the same underlying understanding of object rotation. The findings yield new insights into the relation between tasks using looking times and behavioral measures as dependent variables, and thus may help to clarify performance differences that have previously been observed in studies with infants and young children.

Keywords: mental rotation, object fitting, spatial development, object motion, eye-tracking, toddlers

Mental rotation – the ability to imagine a rotational movement of an object in 2- or 3-dimensional space – has been thoroughly investigated in adults since the early 1970s (Cooper & Shepard, 1973; Shepard & Metzler, 1971). In classic mental rotation tasks, participants are asked to decide whether a rotated image is the same as a comparison image or a mirror reflection. Mental rotation may also be a prerequisite for basic cognitive tasks, such as recognizing a familiar object in an unfamiliar orientation (cf. Tarr & Pinker, 1989).

Developmental research on this topic, however, has faced a challenging dilemma. Whereas recent research suggests that very young infants are able to infer what an object looks like in a different orientation, many children up to the age of 4 or 5 years perform near chance level when using classic mental rotation tasks (Frick, Möhring, & Newcombe, 2014).

Similar discrepancies between reports of amazing abilities in infants and profound lacks in older children have also been shown with regard to perspective taking abilities, metacognitive knowledge (“Theory of Mind”), and intuitions about the laws of physics (for reviews, see Keen, 2003; Perner & Roessler, 2012). These paradoxical results have raised questions of how performance relates to competence, and of whether the same kind of knowledge is measured in studies with different age groups that use different tasks. Do the different tasks tap entirely different knowledge systems? Do these discontinuities reflect a U-shaped development of one single ability that temporarily gets lost and is reacquired years later? Or do they rather reflect changes in representational strength or format, such that knowledge becomes more and more accessible and explicit (cf. Frick et al., 2014; Hespos & Baillargeon, 2008; Karmiloff-Smith, 1994)?

The aim of the present study is to unravel these discrepancies by systematically testing the same toddlers with different tasks and assessing their performance by means of multiple indices. This will increase our understanding of whether infants and young children can form and transform mental representations of objects. In a larger context, getting a better

idea of how results obtained using different paradigms are related will also be highly relevant for infant research in general. As Keen (2003, p. 79) pointed out: “this paradox must be resolved before a comprehensive theory of early cognitive development can be constructed”. The following sections will give an overview of what different research methods have revealed about how the understanding of object rotation develops on different levels of sophistication.

Observation of rotation

Eye-tracking studies have shown that already in the first months of life, infants can follow a moving object with their eyes (e.g., Rosander & von Hofsten, 2002; Rüttsche, Baumann, Jiang, & Mojon, 2006). Infants can also track a small object that moves along a circular trajectory but stays in an upright orientation (Gredebäck, von Hofsten, Karlsson, & Aus, 2005). However, circular tracking seems to be more difficult for infants than tracking linear horizontal or vertical motion (Grönqvist, Gredebäck, & von Hofsten, 2006). Less is known about how tracking of rotation develops. Rotational motion is characterized by an object that changes its own orientation (e.g., a ‘p’ that rotates 180° and then looks like a ‘d’). There are several possibilities for how to observe rotational motion. One possibility is to focus on a point on the rotating object at a certain distance to the pivot point and to follow this point as it moves. This could yield valuable information about the circular trajectory of that particular point. Another possibility is to look only at the stationary pivot point. Yet another option is to switch between the pivot point and points on the object, which could be informative with respect to the changes in orientation of the object. To date, it is unclear which possibility toddlers use when observing rotational motion, and whether gaze patterns change with age.

Anticipation of rotation

Infants not only follow a moving object with their eyes; they have also been shown to look predictively to the location where a linearly moving object would reappear after a short occlusion (e.g., Bertenthal, Gredebäck, & Boyer, 2013; Johnson & Shuwairi, 2009; van der Meer, van der Weel, & Lee, 1994; von Hofsten, Kochukhova, & Rosander, 2007; Woods, Wilcox, Armstrong, & Alexander, 2010). This suggests that they are capable of forming a mental representation of the objects and its movement. At 9 months of age, infants even anticipate the reappearance of an upright object that moves on a *circular* trajectory and is briefly hidden by an occluder (Gredebäck, von Hofsten, & Boudreau, 2002). However, these anticipatory gaze shifts are not yet fully developed, as they still occur less often than in adults (Gredebäck et al., 2002) and become more frequent between 6 and 12 months of age (Gredebäck & von Hofsten, 2004). It is therefore likely that predictive eye movements develop further during toddlerhood and generalize to more complex types of motion, such as rotational movement.

Mental rotation

What might constitute an even more sophisticated type of mental representation is the ability to mentally simulate a rotation precisely enough, so that one knows exactly how a shape would look in a new orientation. For example, when a 'p' is rotated 90° clockwise, one might not only expect that the stem will have a horizontal orientation, but the round part of the 'p' should also face downwards rather than upwards. In other words, the internal spatial relations of the shape should be preserved despite the change in orientation. This ability is typically what is tested in *mental rotation* tasks for older children and adults that require mirror image discrimination (e.g., Kosslyn, 1980; Shepard & Metzler, 1971).

Between the fifth and sixth birthday, children can solve most mental rotation tasks (Estes, 1998; Foulkes & Hollifield, 1989; Frick, Daum, Walser, & Mast, 2009; Frick, Ferrara,

& Newcombe, 2013; Frick, Hansen, & Newcombe, 2013; Krüger & Krist, 2009; Marmor, 1975, 1977; Noda, 2010; Quaiser-Pohl, Rohe, & Amberger, 2010). However, they still have difficulties with some tasks (Dean & Harvey, 1979; Hawes, LeFevre, Xu, & Bruce, 2015), suggesting that mental rotation is not yet fully developed. Between the fourth and fifth birthday, children reached an overall accuracy of 60 to 80% in most studies with two response choices (Estes, 1998; Frick, Hansen, et al., 2013; Noda, 2010; Wimmer, Maras, Robinson, & Thomas, 2016). At disparities between 90 and 135°, the 4-year-olds solved 60% of the trials or more correctly (Frick, Hansen, et al., 2013; Marmor, 1977; Noda, 2010). However, a study with three response choices did not find evidence for mental rotation in 4-year-olds (Quaiser-Pohl et al., 2010). Below 4 years of age, research is sparse. In studies that reported accuracy for each disparity separately, the children performed near chance at disparities of 60° to 180° (Frick, Ferrara, et al., 2013; Frick, Hansen, et al., 2013; Noda, 2010), suggesting that 4 to 4.5 years is about the lower limit for children to succeed in classic forced-choice mental rotation tasks that present mirror images.

On the other hand, mental rotation abilities have also been investigated in infants, using looking time methods (e.g., Frick & Möhring, 2013; Frick & Wang, 2014; Hespos & Rochat, 1997; Möhring & Frick, 2013; Moore & Johnson, 2008; Quinn & Liben, 2008; Rochat & Hespos, 1996; Schwarzer, Freitag, Buckel, & Lofruth, 2012). For example, Möhring and Frick (2013) presented an object in the form of a 'p' or a 'q', which disappeared behind an occluder and reappeared either in its original form or mirror reversed, in an orientation that varied between 0 and 180°. Infants looked longer when the object that reappeared was mirrored than when it was the same as before the occlusion. This suggests that they anticipated how the object would look after the occlusion by means of mental rotation, and that the mirrored object violated this expectation. These and other results from infant research are hard to reconcile with the above-mentioned findings of pronounced

difficulties with behavioral mental rotation tasks in 3- to 4-year-olds. Therefore, it is still an open question how mental rotation develops during the first years of life and through the preschool years.

Physical rotation

Another way to gain insight into toddlers' understanding of rotation is to study how they interact with objects. For example, object-fitting tasks can not only yield valuable information on toddlers' action competencies, they can also shed light on whether toddlers understand and know in advance how they need to rotate an object in order to fit it through an aperture. In a study with 14- to 26-month-olds, Örnkloo and von Hofsten (2007) presented elongated wooden blocks varying in shape, which had to be inserted into a box through various holes. A striking result was that with increasing age, the toddlers more often preadjusted the wooden blocks before they tried to insert them, in that they brought them into the correct orientation already before or during the approach to the hole. Similar results have been obtained in other object-fitting studies (Jung, Kahrs, & Lockman, 2015, 2018; Smith, Street, Jones, & James, 2014; Street, James, Jones, & Smith, 2011), for a review see Lockman, Fears, and Jung (2018). Taken together, the findings of more preadjustments with increasing age demonstrate that toddlers increasingly plan ahead and know in advance *that* and *how* they have to rotate an object to fit it into an aperture.

The present study

In the present study, we investigated whether object-fitting abilities are associated with changes in eye movements during visible rotation, anticipatory eye movements, and mental rotation, by presenting an eye-tracking task and an object-fitting task to the same toddlers. In the eye tracking task, toddlers were presented with computer animations of a shape that looked like the letter 'p', which rotated clockwise and disappeared behind an occluder. Then, the original shape or its mirror version reappeared on the other side of the

occluder. Occluder size and velocity of the rotating shape were varied, and thus the duration the shape was fully occluded, to ensure that the results would generalize to different situations.

First, we measured toddlers' eye movements during the visible rotation before the occlusion, with the aim to explore how toddlers encoded the visible rotation, without having a specific hypothesis. Second, we measured toddlers' eye movements when the shape had disappeared behind the occluder. We hypothesized that with increasing age, toddlers would show more anticipatory looks to the reappearance side of the occluder, as their representation of the object motion and thus their expectation about *where* the object would reappear becomes stronger. Conversely, we also expected that with increasing age, toddlers would less often look back to where the object had disappeared. Third, with respect to mental rotation, we hypothesized that, if toddlers were able to mentally rotate the object and thus had a clear expectation of *how* the object would look after the occlusion, they would respond with prolonged looking times when the mirrored rather than the original shape reappeared, as this would violate their expectation of object constancy. If, however, infants did not form a clear expectation of how the object should look after the hidden rotation, no differences in looking times between mirrored and original shape could be expected.

In the object-fitting task, which was inspired by Örnkloo and von Hofsten (2007), we addressed the question of whether toddlers understand how an object needs to be rotated physically to fit through an aperture. We hypothesized that toddlers would preadjust the wooden blocks more frequently and insert them more often successfully with increasing age. Crucially, based on the assumption that both paradigms tapped the same underlying understanding of object rotation, we hypothesized that measures of both tasks would correlate.

Method

Participants

The final sample consisted of 44 healthy and full-term toddlers (20 girls, 24 boys) between 22 and 38 months of age ($M = 2.56$ years, $SD = 0.42$). Age was used as a continuous variable for statistical analyses, but as categorical variable for some data visualizations, with the age groups of 2 years, 2.5 years, and 3 years (\pm two months).

Data of 5 additional toddlers were excluded from the analyses because they did not want to wear a sticker on the forehead for the eye-tracking, removed it accidentally, or covered it often with the hand. Data of 8 additional toddlers were excluded because they did not pass the eye-tracking inclusion criteria that are described in detail below.

The toddlers were predominantly from middle-class families and lived near or in a small city in Switzerland. They were recruited in day-care centers, courses, parks, or through the website of the lab. When the child was in the right age range, parents were contacted telephonically and informed about the study. The children were tested in German or French. The parents gave informed, written consent prior to the study. After the study, the toddlers received a certificate and a small gift, such as a toy car or a bubble wand. The study followed ethical guidelines and was approved by the Internal Review Board of the University of Fribourg (project; *Development of Spatial Thinking*, protocol number: 154).

Power analyses were computed in R (package: *pwr*) to check whether a sample size of 44 participants is sufficiently large to test our hypotheses. The main goals of this study were to detect effects of age, which was used as a continuous variable, as well as correlations between different indices. Power analyses showed that with 44 participants, a power of .80 or more can be reached with a correlation of $r > .40$. Thus, the sample size was large enough to detect medium correlations. Another goal was to detect effects of within-participant variables with two levels (e.g., original vs. mirror object). In a general linear model, a power of .80 or

more can be reached for medium within-participant effects ($d \geq .43$). Thus, the sample size was also large enough to test our hypotheses with regard to within-participant effects.

Eye-Tracking Task

Test environment and apparatus. The experiment took place in a dimly lit room. The room was divided into a section for the participants (170 x 170 cm) and a section for the experimenter. The participant section was enclosed by a black curtain and contained a chair, a computer screen, an eye-tracking camera with illuminator, and a video camera. The toddlers were seated in front of the computer screen (ASUS, ROG Swift PG278Q, 27", 2560x1440, 100 Hz) either on the parent's lap or in a slightly reclined child car seat. In the latter case, the parent was standing behind, outside of the child's viewing range. The distance between the toddler's forehead and both the eye-tracker camera and the participant screen was approximately 60 cm. The participant screen was slightly tilted so that it was perpendicular to the toddler's line of sight.

The experimenter controlled the experiment from behind the curtain. The experiment was run using Matlab software (R2012a) with Psychtoolbox 3.0.9 (Kleiner et al., 2007) and Eyelink Toolbox (Cornelissen, Peters, & Palmer, 2002) on a PC with Windows 7. An *EyeLink 1000 Remote* Eye-tracker (SR Research) recorded the toddler's eye movements at a temporal resolution of 500 Hz. A small sticker was attached to the toddler's forehead, so that the gaze position could be computed despite of head movements. The eye-tracking camera with an 890-nm-illuminator was placed below the participant screen. Saccades (rapid, abrupt eye movements) and blinks were detected using Eyelink's standard thresholds (parameter settings: saccade velocity threshold = $30^\circ/\text{s}$, saccade acceleration threshold = $8000^\circ/\text{s}^2$, saccade motion threshold = 0.1° , blink offset verify time = 12 ms).

Below the participant screen and adjacent to the eye-tracker camera, there was a second camera – a video camera with infra-red function (Sony, DCR-AX33). It was linked to

a control monitor behind the curtain, so that the experimenter could see the toddler. The camera also recorded the video for offline coding of looking time.

Procedure. The parent was thoroughly informed about the study and instructed not to talk to the toddler during trials, and to either close the eyes or to look at the back of the toddler's head during trials. As soon as the toddler and the parent had entered the room, an animation with animals started playing on the participant screen. The toddler sat down, and the sticker for the eye-tracking was attached on the toddler's forehead. If necessary, the toddler was distracted from the sticker placement with a small snack. The seat position and the eye-tracking settings were adjusted, the room lighting dimmed, and the curtain around the participant section closed. A five-point calibration with animated stars that changed in size and color was performed. After the calibration, an abstract flower image followed by a short animation with an octopus were shown in the center of the screen. The set-up took approximately three minutes.

Each toddler was presented with two familiarization trials and four test trials in immediate succession. All trials followed the same general procedure: A pulsating and color-changing star that was accompanied by cheerful music directed the toddler's attention to the center of the screen. As soon as the toddler looked at the star, the experimenter started a computer animation of a rotating shape on a black background (see below). During this animation, the experimenter pressed a computer key whenever the toddler looked at the screen. The trial was terminated (with a short beeping sound) when the key was released for 2 consecutive seconds or a time-out (see below) was reached.

Familiarization trials. The two familiarization trials featured a magenta stimulus in the shape of the letter 'T' (see Figure 1A). The lower end of the stem was used as the pivot point when rotating the shape. The stem tapered towards the lower end, so that the pivot point was clearly defined. The pivot point was at the center of the screen. The 'T' had a height of 9

cm and a width of 35° (i.e., the angle between the left side, the lower end, and the right side of the 'T' was 35°). Thus, when the stimulus rotated 35° around its foot, it completely changed location.

The first familiarization trial showed a fully visible rotation. The computer animation began with a short beep. The stimulus was in an upright position (0°) for the first 2 s and then rotated 310° clockwise, stopped, and remained visible. Rotation velocity was $60^\circ/\text{s}$ for toddlers in the fast-velocity group or $30^\circ/\text{s}$ for toddlers in the slow-velocity group. Measurement of looking time began when the stimulus was 40° away from its end position (for the sake of comparability with occluded trials); the trial was ended when the toddler had looked away for 2 consecutive seconds, or when 10 s had elapsed.

In the second familiarization trial, an occluder was introduced (see Figure 1A, first row). Again, the computer animation started with a beep. The 'T' was presented in upright orientation, remained there for 2 s, and then started rotating. The stimulus then disappeared behind the occluder, which was grey, shaped like a piece of pie, and covered an angle of 117.5 to 227.5° (medium occluder). During the full occlusion, the stimulus was completely covered, as its stem tapered towards its lower end. After the stimulus had fully reappeared, it rotated 5 more degrees, stopped moving, and remained visible. Measurement of looking time started at the end of the full occlusion, just when the stimulus started reappearing (i.e., 40° away from the end position). From this timepoint on, the trial ended when the toddler had looked away for 2 consecutive seconds or when 10 s had elapsed. Familiarization trials were repeated immediately (maximally twice) if the toddler looked at the participant screen less than 75% of the time, counted from the start of the trial until 2 s after the end of the full occlusion.

Test trials. The four test trials had the same event structure as the second familiarization trial, except that the time-out was at 30 s instead of 10 s. In test trials, the

rotating shape resembled the letter 'p', had a height of 9 cm, a width of 35°, and a stem that tapered towards the lower end (see Figure 1A). The color of the 'p' was red, green, blue, and yellow in the trials 1, 2, 3, and 4, respectively. Thus, each toddler saw the colors in the same order. As in familiarization trials, velocity was 60°/s in the fast-velocity group and 30°/s in the slow-velocity group.

The four trials varied in occluder size (small / big) and the reappearing shape after the occlusion (original / mirror version). The small occluder (see Figure 1A, second row) had the disappearance side at 117.5° and the reappearance side at 212.5°, thus covering an angle of 95°. In this case, the stimulus rotated 60° under full occlusion, with a full occlusion duration of 1 s (fast velocity) or 2 s (slow velocity). The big occluder (see Figure 1A, third row) had the disappearance side at 117.5° and the reappearance side at 242.5° and thus covered an angle of 125°. In this case, the stimulus rotated 90° under full occlusion, with a full occlusion duration of 1.5 s (fast velocity) or 3 s (slow velocity). Each occluder size was shown twice to a participant: once, the shape that reappeared was the same as before the occlusion ('p'), and once, it was mirrored and thus looked like the letter 'q'. It was counterbalanced between toddlers in which order they saw the two occluder sizes (small-small-big-big or big-big-small-small for the test trials 1 to 4, respectively), and in which order they saw the shapes after the occlusion (different-same-same-different or same-different-different-same). The toddlers were randomly assigned to these orders as well as the velocity conditions while making sure there were about equal numbers per age group and sex. The test trials were never repeated.

Data analysis. After each session, eye-tracking data was inspected for quality. For each single trial, the raw gaze positions were animated together with the stimuli to check whether the eye movements were properly recorded. This also provided initial information on what types of eye movements toddlers exhibited during different parts of the animation.

These mainly consisted of smooth pursuit eye movements, saccades between the stimulus and the pivot point, and saccades to the reappearance side of the occluder.

Areas of interest. The visual inspection of single trials had shown that during the visible rotation, children looked mostly at the rotating stimulus or the pivot point. During the full occlusion, they looked mostly either at the disappearance side of the occluder, the pivot point, or the reappearance side of the occluder. For this reason, five areas of interests (AOIs) were defined. The *scene AOI* covered the entire scene and was a circle with a radius of 13 cm, in the center of the screen. This radius was 3 cm larger than the radius of the occluder, allowing a margin of measurement error of up to 3 cm. The other AOIs all lay within the scene AOI. The *pivot AOI* was a circle with a radius of 3 cm, also in the center of the screen. The *disappearance AOI* covered the disappearance side of the occluder and looked like a piece of pie. It had a width of 70° , which was twice the width of the stimulus. It covered only those areas of the occluder that had a distance of 3 cm to the center of the screen. Thus, it did not overlap with the pivot AOI. The *reappearance AOI* had an identical shape but covered the reappearance side of the occluder. The 3-cm-criterion that defined the radius of the pivot AOI was a conservative choice and ensured that looking at the pivot point with a measurement error of up to 3 cm could not be misinterpreted as a predictive eye movement to the reappearance AOI. The last AOI was the *stimulus AOI*. Unlike the other AOIs, the stimulus AOI was not static, but rotated together with the stimulus. It was also shaped like a piece of pie. It had a width of 70° , a radius of 12 cm (3 cm longer than the stimulus size) and did not overlap with the pivot AOI. Since the stimulus AOI rotated together with the stimulus, it could sometimes overlap with the disappearance or reappearance AOI.

Inclusion criteria. To make sure to include only trials in which the toddlers had seen critical parts of the animation, trials were classified as valid or invalid with an algorithm written in Matlab. Since toddlers made smooth pursuit eye movements as well as saccades,

inclusion criteria were based on raw gaze positions. To ensure that the inclusion criteria were appropriate, they were not only theoretically motivated, but additionally informed by inspecting the animations of single trials. A trial was valid if it fulfilled the following four criteria. (1) *The toddler had encoded the stimulus*: In a time window from the start of the trial until the start of full occlusion, the toddler's gaze was on the stimulus AOI for at least 1 s. (2) *The toddler had seen the rotation*: In a time window from the start of rotation until the start of full occlusion, the toddler looked at the stimulus or pivot AOI for at least 33% of the time. (3) *The toddler was attentive directly before the occlusion*: In a time window of 1 s before the beginning of the full occlusion, the toddler looked at least 200 ms at the stimulus, pivot, or disappearance AOIs. (4) *The toddler was attentive after the occlusion*: Within 1.5 s after the end of the full occlusion, the toddler looked at least 200 ms at the stimulus, pivot, or reappearance AOIs. The time window for this criterion was 0.5 s longer than for criterion 3, because we assumed that some attentive toddlers would still be looking at the disappearance AOI when the stimulus started reappearing, and we wanted to give them enough time to switch their gaze to the stimulus, pivot, or reappearance AOI. A toddler's data was included if at least three out of the four test trials concurred with the inclusion criteria. The 8 children who were excluded from the analyses did not pass the inclusion criteria due to looking away or to the parent, changes in head position, half-closed eyes, or pointing at the screen with the hand. For 37 out of the 44 included children, all four trials were valid.

Calibration accuracy. The average calibration error for the included toddlers was 0.82 visual degrees. This corresponded to an average horizontal error of 0.58 cm ($SD = 0.26$) and an average vertical error of 0.60 cm ($SD = 0.27$), which can be considered small with respect to the sizes of the AOIs. The horizontal error did not correlate with age ($r = .09$, $p = .55$), nor did the vertical error ($r = .07$, $p = .65$).

Wooden Block Task

Stimuli and apparatus. After the eye-tracking task, the toddlers took a short break and then participated in the wooden block task, which took place in a bright room. The toddlers were seated at a rectangular table, either on a chair or on the parent's lap. The experimenter sat at the left side of the table from the child's point of view. Two video cameras filmed the experiment: the main camera was located opposite to the participant; the second camera was placed at the right side of the table. Stimuli were stored beneath the table, outside of the child's view. The parents were instructed to not help the toddlers, but they could encourage and praise the toddlers.

The stimuli consisted of 16 wooden blocks, which were elongated objects that varied in length and in the shapes of their bases (Figure 1C). The term 'base' can be defined as the side of the object that is perpendicular to its longest extension; for example, in a cylinder, the base is a circle. The wooden blocks had to be inserted vertically into a box through apertures that corresponded in shape to the bases of the blocks (Figure 1D). A cylinder, for example, had to be inserted through an aperture that had the shape of a circle.

The wooden blocks varied on four difficulty levels. Two blocks were of *very easy* difficulty: they had a circular base, with a diameter of 3.4 cm; one was 6 cm and the other 9 cm long. Two blocks with square base (2.9 x 2.9 cm) were considered *easy*; one was 6 cm and the other 9 cm long. The *medium* difficulty level consisted of 6 blocks, with 3 bases (oval, rectangle, hexagon) and 2 lengths (6 or 9 cm). These bases were mirror-symmetrical along two axes. Thus, when the blocks were upright, they could be inserted in two ways into the corresponding aperture: the base could have a disparity of either 0 or 180° with respect to the aperture. The *hard* difficulty level consisted of 6 wooden blocks, with 3 bases (semi-circle, isosceles triangle, isosceles trapezoid) and 2 lengths (6 or 9 cm). The bases of these blocks had mirror-symmetry along only one axis, and thus the blocks could be inserted in

only one way when upright: the base had to have a disparity of 0° with respect to the aperture. The bases of medium and hard blocks measured roughly 4.2 x 2.3 cm.

The wooden box in which the blocks had to be inserted was 19.8 cm wide and deep, and 13.8 cm high. The inside was covered in black foam rubber to soften the impact when the blocks were jolted into the box. A large aperture on the left side allowed the experimenter to remove the blocks after a trial. Exchangeable lids could be placed on the top, each with an aperture in its center that corresponded to the base of a wooden block. The lids were made of plywood and covered with beige foam rubber. The lids were oriented such that the blocks would fit if oriented as depicted in Figure 1C from the child's point of view. The box was approximately 15 cm below the child's eye-level, so that the child could clearly see the shape of the apertures. The wooden blocks were presented on a black cuboid, which was placed behind the box, from the toddler's viewpoint. It had the same width as the box, but was 5 mm higher and 11.5 cm deep.

Procedure. Each toddler was presented with the same order of trials (see Table 1): 2 training trials (easy), 6 test trials (medium and hard), 2 baseline trials (very easy), and another 6 test trials (medium and hard). At the start of the experiment, the experimenter explained to the toddler that the game was about sticking blocks into the box, demonstrated with a training stimulus how to insert it into the aperture, and then let the toddler insert both training stimuli. After the toddler had successfully inserted both training stimuli, the test trials began.

At the beginning of each trial, the experimenter placed the lid on the box and the wooden block on the pedestal in one of two possible *orientations* (see Table 1). The orientations had in common that the block was placed flat, diagonally on the pedestal (Figure 1D). In one orientation, the block's longitudinal axis extended from close left to far right from the toddler's viewpoint ($+45^\circ$), and in the other orientation, it extended from close right to far left (-45°). The experimenter held the wooden block slightly at the far end and asked

the toddler: “How does this one fit through the hole?” The experimenter then released the block, so that the toddler could grasp it. If the toddler successfully inserted the block into the aperture (see also criteria for success below), the experimenter praised the toddler and confirmed: “Yes, that’s the way it fits through the hole!” If necessary, the toddlers were asked to try again, and if they did not succeed within 20 s after touching the block for the first time, the experimenter helped inserting the block. This ensured that each toddler was provided with the same feedback regardless of success. After each trial, the experimenter removed the block and lid.

Results

The eye-tracking data were analyzed based on *raw* gaze positions (without saccades or blinks), because the toddlers not only looked at static parts of the scene such as the pivot point or the occluder, but also often tracked the rotating stimulus with slow eye movements (smooth pursuit). In addition to raw gaze positions, saccades were analyzed in order to count how often the toddlers switched between AOIs. A switch was defined as a gaze shift between two AOIs with at least one saccade in between.

General visual attention

On average, the 44 toddlers looked at the scene AOI in 90% of the time, measured from the start of the animation until 1.5 seconds after the end of the full occlusion. The remaining 10% consisted of saccades, blinks, looking away, or other kinds of data loss. An ANCOVA showed that age (mean-centered covariate) and velocity (fast / slow) had no main effects on the percentage of time the toddlers looked at the scene AOI (both $F_s < 1$). Age interacted with velocity, $F(1, 40) = 4.93, p = .03, \eta_p^2 = .11$. Post-hoc linear regressions showed that age effects went in opposite directions in the two velocity conditions, but both effects were not significant (in the fast-velocity condition: $b = 7.08, p = .08$; in the slow-velocity condition: $b = -4.81, p = .18$).

Observation of rotation

To explore how the toddlers observed the rotating shape, the data during the fully visible rotation before the occlusion were analyzed. The toddlers looked mostly at the stimulus AOI, but also attended the pivot point (see Figure 2). In the fast velocity condition, they looked in 69% of the time at the stimulus AOI ($SD = 17$) and in 20% of the time at the pivot AOI ($SD = 15$). Similarly, in the slow velocity condition, they looked in 64% of the time at the stimulus AOI ($SD = 16$) and in 20% of the time at the pivot AOI ($SD = 14$).

The toddlers also switched between looking at the stimulus AOI and the pivot AOI. In the fast velocity condition, they switched 0.53 times per trial ($SD = 0.33$) from the pivot to the stimulus AOI, and 0.27 times per trial ($SD = 0.26$) from the stimulus to the pivot AOI. In the slow velocity condition, they switched 0.8 times per trial ($SD = 0.5$) from the pivot to the stimulus AOI, and 0.65 times per trial ($SD = 0.48$) from the stimulus to the pivot AOI.

Next, we explored how these four measures were related among each other. All intercorrelations were controlled for velocity. Looking at the stimulus AOI was negatively correlated to looking at the pivot AOI ($r = -.79, p < .001$). Looking at the stimulus AOI was also negatively correlated to switches from the stimulus to the pivot AOI ($r = -.45, p = .002$) and to switches in the other direction ($r = -.46, p = .002$). Looking at the pivot AOI, switches from the stimulus to the pivot AOI, and switches from the pivot to the stimulus AOI were all positively intercorrelated (all $r_s > .49$, all $p_s < .001$). These correlations suggested a trade-off between following the stimulus AOI versus looking at the pivot AOI and switching to and from the pivot AOI. Visual inspection of the data confirmed that some children looked almost exclusively to the stimulus AOI, whereas some children distributed their gaze about equally between the stimulus and the pivot AOI. Most children were somewhere in between these extremes and showed a combination of mostly tracking the stimulus but also attending to the pivot point. No toddler looked exclusively at the pivot point, as all toddlers looked at the

stimulus AOI in at least 33% of the time.

Possible age-related changes in how the toddlers observed the visible rotation were analyzed by means of ANCOVAs, with velocity (fast / slow) as between-participants variable and age as mean-centered covariate. Separate ANCOVAs were performed for each of the four dependent variables separately. A first analysis revealed that with increasing age, the toddlers looked less long at the stimulus AOI, $F(1, 40) = 4.51, p = .04, \eta_p^2 = .10$. Neither the main effect of velocity nor the interaction term was significant (both F s < 1). A second analysis showed that with increasing age, the children switched more often from the stimulus to the pivot AOI, $F(1, 40) = 4.57, p = .04, \eta_p^2 = .10$. Velocity had a significant main effect, $F(1, 40) = 11.36, p = .002, \eta_p^2 = .22$, but did not interact with age ($F < 1$). A third ANCOVA showed that neither age nor velocity had an effect on the percentage of the time the toddlers looked at the pivot AOI, all F s(1, 40) ≤ 1.10 , all p s $\geq .30$. A fourth ANCOVA showed that age did not influence how often the toddlers switched from the pivot to the stimulus AOI ($F < 1$), but that switches in this direction were more frequent in the slow than the fast velocity condition, $F(1, 40) = 4.44, p = .04, \eta_p^2 = .10$, without interacting with age ($F < 1$). To summarize, the toddlers looked significantly less long at the stimulus AOI and switched more often from the stimulus to the pivot AOI with increasing age, see Figure 3A and 3B.

Anticipation of rotation

Figure 2 suggests that with increasing age, the toddlers looked more anticipatorily to the reappearance AOI. To test this statistically, *arrival times* were computed, using a time window that consisted of the full occlusion plus 1.5 s, in order to include the data of toddlers who only shifted their gaze in response to the reappearing stimulus. Time zero was defined as the time when the full occlusion ended; negative values indicated anticipatory eye movements. For example, an arrival time of -0.5 s would indicate that gaze arrived at the reappearance AOI half a second before the stimulus started reappearing. Arrival time could

be computed for all trials that had passed the inclusion criteria, except for two trials in which the gaze never arrived at the reappearance AOI in the given time window. These two trials were excluded.

Developmental changes in arrival times were analyzed with a repeated-measures ANCOVA. The independent variables were velocity (between-participants, fast / slow) and occluder size (within-participant, small / big). Age was entered as a covariate (continuous and mean-centered). Velocity as well as occluder size had significant main effects on arrival time: toddlers' gaze arrived more in advance when the velocity was slow compared to fast, $F(1, 40) = 29.70$, $p < .001$, $\eta_p^2 = .43$, and when the occluder size was big compared to small, $F(1, 40) = 13.58$, $p < .001$, $\eta_p^2 = .25$. Velocity and occluder size did not interact ($F < 1$). As expected, age had a significant effect on arrival time (see Figure 3C): with increasing age, gaze arrived earlier at the reappearance AOI, $F(1, 40) = 8.55$, $p = .006$, $\eta_p^2 = .18$. The age effect was similar in all conditions, as there were no significant interactions with velocity and/or occluder size (all F s < 2.24 , all p s $> .13$). Table 2 illustrates that the 2-year-olds' gaze arrived at the reappearance AOI approximately when the stimulus started reappearing if occlusion duration was 1 s, but clearly in anticipation of the stimulus if occlusion duration was 3 s. The 3-year-olds showed clear anticipatory eye movements in all conditions.

To test whether age differences in anticipatory eye movements were not just due to development in speed, but that younger children less clearly expected the stimulus to reappear at the reappearance side, we tested whether younger children looked back to the disappearance side more often. Looking back was defined as a switch (see above) to the disappearance AOI, from either the pivot AOI, the reappearance AOI, or the area of the occluder between the disappearance and reappearance AOI. Because the toddlers rarely looked back in the fast-velocity condition, in which occlusion duration was likely too short to look back, only the data of the slow-velocity condition were analyzed. On average, the

toddlers looked back 0.36 times per trial ($SD = 0.31$). Linear regression revealed that with increasing age, the toddlers looked back significantly less often ($b = -0.47$, $p = .003$; see Figure 3D). Figure 2 also shows that looks to the disappearance AOI near the end of the occlusion phase decrease with age.

Mental rotation

As an indicator for mental rotation, *looking time* was analyzed. Looking time was defined as the cumulative time of looking at the scene AOI after the end of the full occlusion, before looking away for 2 consecutive seconds or the time-out was reached. Looking time was coded manually in *Datavyu* Software (Datavyu Team, 2014). To assess reliability, looking time was also computed using the raw eye-tracking gaze positions, which showed a strong correlation with the manually coded looking times ($r = .95$).

To test whether the toddlers looked longer at the scene when the shape that reappeared was the mirror image rather than the original shape, looking times were analyzed with a multilevel model (*R*-package: *afex*; function: *mixed*). The fixed effects were the shape after the occlusion (within-participant, original / mirror image), occluder size (within-participant, small / big), velocity (between-participants, fast / slow), and age (continuous and mean-centered). The model included random intercepts. Results showed that looking times were similar when the shape after the occlusion was the original ($M = 8.66$ s, $SD = 5.53$) and when it was the mirror image ($M = 7.74$ s, $SD = 5.16$), and there were no other significant main effects or interactions (all F s < 1.64 , all p s $> .19$). Looking times did thus not provide evidence for mental rotation in the tested age range.

Wooden block task

For the wooden block task, we report the data of the 44 children who were included in the eye-tracking task. For these children, all trials of the wooden block task were analyzed. Videos were coded using the *Datavyu* software. The start of a trial was defined as the point in

time when the toddler touched the wooden block the first time.

Preadjustment. To test whether the toddlers knew in advance how they needed to rotate the wooden blocks before trying to fit them through the apertures, preadjustments were analyzed. Analysis of preadjustment was based on the point in time when the wooden block was both *upright* and *placed near or on the aperture* for the first time. Being upright was defined as deviating less than 30° from vertical. To code whether the block was placed near or on the aperture, a rectangular AOI on the box's lid was defined, which covered the aperture and a margin: each of the AOI's four sides was located at a third of the distance between the border of the aperture and the side of the box. A wooden block was considered as placed near or on the aperture when a part of it touched the lid within the AOI or – if directly over the hole – had the same altitude as the lid's surface. Inter-rater reliability for determining the point in time when the block was for the first time both upright and placed near or on the aperture was excellent ($r = .97$). At this timepoint, a wooden block was considered *preadjusted* if the orientation of its base differed maximally 30° from the aperture's orientation. This could be coded for all trials, except for one in which the block was never both upright and placed near or on the aperture. This trial was coded as not preadjusted. Two independent raters agreed in 97% of the trials whether the block was preadjusted or not.

A repeated-measures ANCOVA on preadjustment was calculated, with difficulty (medium / hard) as within-participant variable and age as covariate (continuous and mean-centered). The analysis revealed a significant effect of difficulty, $F(1, 42) = 41.13, p < .001, \eta_p^2 = .49$ (Figure 4A). The toddlers preadjusted the medium blocks in 76% of the trials ($SD = 23$), and the hard blocks in 43% of the trials ($SD = 27$). (This effect was expected, as blocks of medium difficulty could be preadjusted in two ways once upright, whereas blocks of hard difficulty could be preadjusted in only one way). Preadjustment increased significantly with

age, $F(1, 42) = 9.41, p = .004, \eta_p^2 = .18$. Age and difficulty did not interact, $F(1, 42) = 1.47, p = .23$.

Success. A trial was coded as successful if the wooden block was inserted at least 1 cm into the aperture within the available 20 s. Two independent raters agreed on 100% of the trials. Because success rate was not normally distributed and had unequal variances across difficulty levels and age, it was analyzed using non-parametric statistics. Overall, the toddlers were highly successful. At medium difficulty, all toddlers had a success rate of 100%, except for one toddler who solved all but one trial successfully. At hard difficulty, the average success rate was 83% ($SD = 24$). The difference between medium and hard difficulty was significant (Wilcoxon signed-rank test: $Z = 3.75, p < .001$). Because the toddlers solved almost all trials of medium difficulty successfully, age effects were investigated at the hard difficulty level (Figure 4D). Toddlers solved significantly more hard trials successfully as age increased (Spearman's $\rho = .59, p < .001$).

For additional information, the time of success was also coded (inter-rater reliability: $r = .98$; see Figure 4B). Age differences could already be observed early in the trial, and the likelihood of solving the task within the first 4 s increased with age (medium difficulty: Spearman's $\rho = .44, p = .003$; hard difficulty: Spearman's $\rho = .33, p = .03$; see Figure 4C).

Correlations among performance measures

To test the hypothesis that predictive eye-movements are related to object-fitting performance, we computed correlations between arrival time in the eye-tracking task and preadjustment as well as success in the object-fitting task. Since the success rate had considerable variance at hard difficulty only, success at hard difficulty was used for correlations. Results showed that there was a significant negative correlation between arrival time in the eye-tracking task and preadjustment in the wooden block task, if controlled for

velocity ($r = -.48, p = .001$) or velocity, age, and how much the children attended to the scene AOI during visible rotation ($r = -.37, p = .018$). The more frequently toddlers preadjusted the objects in the wooden block task, the earlier they looked to the reappearance AOI in the eye-tracking task (Figure 5). There was no correlation between arrival time in the eye-tracking task and success at hard difficulty in the wooden block task, Spearman's $\rho = -.14, p = .38$.

Finally, we explored all other possible correlations of measures within and between tasks. For the eye-tracking task, these were the four measures of how the children encoded the visible rotation (looking at stimulus AOI, looking at pivot AOI, switches from stimulus to pivot AOI, switches from pivot to stimulus AOI) as well as arrival time, looking back to the disappearance AOI, and looking-time differences between the mirror object and the original object. As mentioned above, the four measures of how the toddlers encoded the visible rotation were significantly intercorrelated. In addition, results showed that the more the toddlers had switched from the stimulus to the pivot AOI during the visible rotation, the earlier their gaze arrived at the reappearance AOI, controlled for velocity ($r = -.48, p = .001$). This correlation remained significant if controlled not only for velocity, but also for age and how much the children looked at the scene AOI during the visible rotation ($r = -.38, p = .01$). Switches in the other direction, from the pivot AOI to the stimulus, during the visible rotation were also related to earlier arrival times, controlled for velocity ($r = -.51, p < .001$). This also remained significant if controlled for velocity, age, and how much the toddlers looked at the scene AOI during the visible rotation ($r = -.46, p = .002$). In addition, there was a nonsignificant trend for earlier arrival time the less toddlers looked at the stimulus AOI during the visible rotation, controlled for velocity ($r = .27, p = .08$). However, arrival time was not correlated with how much the toddlers looked at the pivot AOI during the visible rotation, controlled for velocity ($r = -.23, p = .14$).

Within the wooden block task, preadjustment and success rates at hard difficulty were

significantly correlated (Spearman's $\rho = .53, p < .001$), even if controlled for age ($\rho = .42, p = .005$). The more often toddlers preadjusted the blocks of hard difficulty, the more often they succeeded at inserting them. There were no other correlations within or between tasks (all $|rs| < .30$, all $ps > .14$).

Additional analyses

Each of the above-mentioned performance measures were also analyzed for sex differences. There were no significant main effects of sex on any of these variables.

Moreover, the statistical results of all parametrical tests were verified using permutation tests, which were programmed in R. A permutation test is a resampling approach that allows for computing p -values without making any assumptions about the underlying distribution of the data. These permutation tests yielded p -values that were very close to the p -values reported above, and using this approach did not change whether any of the observed results reached statistical significance (at $p < .05$) or not.

Discussion

In this study, we investigated toddlers' understanding of rotational object movement. We measured how they observe a rotating shape, whether they anticipate an observed rotational movement, whether they know in advance how they need to rotate an object to fit it through an aperture, and whether they can mentally rotate an object. Overall, the results showed marked changes in several of these skills between 2 and 3 years of age, suggesting pronounced developmental progression in toddlers' cognition about object rotation. Moreover, switches between the stimulus and the pivot point during visible rotation were associated with anticipatory looking, which in turn was related to toddlers' preadjustments of wooden blocks in the object fitting task, suggesting a tight relation between visual processing of rotational object movement and action competencies.

Observation of rotation

The eye-tracking results during the visible rotation showed that with increasing age, the toddlers looked less exclusively to the stimulus and switched more often from the stimulus to the pivot point. Thus, rotational motion evoked more complex eye-movement patterns than previously observed with upright objects moving on a circular trajectory (e.g., Gredebäck et al., 2005). Since motion attracts attention (e.g., Franconeri & Simons, 2003), looking less exclusively at the rotating stimulus might involve an active disengagement process. With increasing age, toddlers might learn to inhibit looking at moving parts of a scene, so that they can more flexibly attend other relevant features. This may provide them with more detailed information on how the shape changes its orientation over time.

Anticipation of rotation

The result that the toddlers looked more anticipatorily to where the rotating object was likely to reappear after the occlusion extends previous findings (e.g., Gredebäck et al., 2002) by indicating that anticipatory eye movements continue to develop during toddlerhood. The finding that the toddlers less frequently looked back to the disappearance AOI with increasing age suggests that anticipatory eye movements did not simply get faster with age, but that the toddlers developed a stronger expectation that the object would reappear at the reappearance side rather than the disappearance side of the occluder.

Mental rotation

The present study also tested mental rotation using a violation-of-expectation paradigm – a looking-time method that has previously provided evidence for mental rotation in 6- to 10-month-old infants (e.g., Frick & Möhring, 2013; Möhring & Frick, 2013). In the present study, however, looking times did not yield evidence for mental rotation in toddlers, and there were no age effects nor correlations of looking-time differences with other dependent variables. This result can be explained in at least three different ways. A first

possibility is that toddlers are not capable of mental rotation. A second possibility is that toddlers can perform a mental rotation, but that they did not do it in the present task – maybe because they did not sufficiently pay attention to whether the shape looked like a ‘p’ or ‘q’, as this was not salient enough or they were busy attending to other features. A third possibility is that the toddlers did perform a mental rotation, but that looking time may not have been an appropriate measure to capture this competence in the present task or for the present age group. Similarly, Langer, Gillette, and Arriaga (2003) did not find significant results in 21-month-olds’ looking times, which contrasted with their successful performance in a search task - but see also He, Bolz, and Baillargeon (2011) for a successful application of a violation-of-expectation paradigm with 2.5-year-olds. Looking times can be influenced by a number of factors and reflect various cognitive processes, such as expectations of what will happen on the screen next, or curiosity about what their parent thinks of the event. We therefore cannot draw any conclusions about whether toddlers are capable of mental rotation on the basis of these non-significant looking-time results.

Physical rotation

In line with previous findings from object-fitting tasks (Jung et al., 2015, 2018; Örnkloo & von Hofsten, 2007; Smith et al., 2014; Street et al., 2011), the toddlers’ preadjustment and success rates in the wooden block task developed considerably between 2 and 3 years of age. This indicates that with age, the toddlers increasingly considered in advance how they needed to rotate the wooden blocks in order to insert them into the apertures.

Preadjustment could be achieved by two different strategies. Using a physical-rotation strategy, the toddler may physically rotate the object (e.g., in the air) and compare it with the aperture. If the comparison indicates that the object is not yet correctly oriented, the steps of rotating and comparing can be repeated, until the comparison indicates that the object is

aligned with the aperture. Alternatively, using a mental-rotation strategy, the toddler may rotate the object mentally and then compare this mental image with the aperture. Both strategies have in common that they require a sophisticated understanding of object rotation, as in both strategies, the toddlers consider how the block has to be rotated before they physically try to insert it. Based on our data, we cannot distinguish between these two strategies with certainty. However, the mental rotation strategy could be expected to be faster than physically acting out each step. Thus, the increasing number of toddlers who already solved the task within 4 s might indicate a development from a slower physical-rotation strategy to a faster mental-rotation strategy between 2 and 3 years of age. Future studies using higher-resolution motion tracking technology may further explore these strategies.

Correlation between encoding of visible rotation and arrival time

In the eye-tracking task, switches between the stimulus and the pivot AOI during the visible rotation (as opposed to extensive tracking of the stimulus) were associated with earlier anticipatory eye movements to the reappearance side of the occluder. This correlation remained significant even if controlled for age, velocity, and how much the toddlers looked at the scene during visible rotation. Thus, general developmental maturation or general visual attention cannot account for the correlation. A precondition for both switches and anticipatory looks is the ability to disengage from looking at one location and to make saccades to another location. Young infants have often been found to stick to an object with their gaze (Hood & Atkinson, 1993). In toddlerhood, the ability to disengage may still be improving and give rise to individual differences. That is, toddlers who are better able to switch their gaze during visible rotation might also be less likely to stick to the disappearance side of the occluder once the object has disappeared, and more likely to shift their gaze across the occluder. A more specific reason for the correlation between switches during visible rotation and arrival time might be that the switches had enabled the toddlers to understand

how the orientation of the object changed as it rotated, leading to a more detailed representation of the object and its movement, and thus to a clearer expectation.

Correlation between arrival time and preadjustment of wooden blocks

As a main finding, the present study showed a significant correlation between anticipatory looks in the eye-tracking task and preadjustments in the wooden block task. This correlation was still significant if controlled for age, velocity, and how much the children looked at the scene AOI during visible rotation. Thus, it is unlikely that general age-related maturation or visual attention had influenced this correlation.

This close relation between anticipatory looks and preadjustment, together with the findings that measures of both tasks underwent considerable development across the investigated age range (i.e., over a period of 16 months), suggests that visual processing of rotational object movement and action competencies develop in parallel. Moreover, the findings of rather sophisticated (but still developing) rotation understanding in toddlerhood render the possibility unlikely that infants are endowed with knowledge that gets lost during toddlerhood and is regained around age 5. The data rather suggest that competencies increase continuously across age.

The correlational findings and the parallel developmental progression thus corroborate the notion that the different measures reflect a common underlying competency. A possible common mechanism underlying predictive eye movements and preadjustments of wooden blocks may be the basic ability to mentally simulate object rotation. In the eye-tracking task, mentally simulating the rotational movement during occlusion might have allowed the toddlers to know where the rotating shape was going to reappear. In the wooden block task, mental simulation might have allowed the toddlers to know in advance how the base of the wooden block needed to be rotated to fit through the aperture.

The finding of a parallel and synchronized development in different performance

measures is also in line with dynamic systems theory of development (cf. Smith & Thelen, 2003), which conceptualizes development as the emergent product of continually linked and mutually interactive processes that occur over time. In accordance with this systemic view, our findings suggest that in order to thoroughly understand developmental processes, it is useful to combine different research paradigms and simultaneously assess multiple performance measures within the same children. Future studies may also attempt to chart the developmental time course of individual measures within children, using longitudinal designs.

Conclusion

The present study showed striking developmental parallels between toddlers' eye movements when observing visible rotation or anticipating hidden rotation, and their ability to preadjust wooden blocks and to fit them successfully into apertures. In all of these areas, some competencies were present at age 2, but they still improved markedly until the age of 3. A common mechanism underlying predictive eye movements and preadjustments of wooden blocks may be the ability to mentally simulate object rotation. The present findings suggest that toddlerhood is an age when broad changes happen in the understanding of object rotation.

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Tables and Figures

Table 1

Order of the trials in the wooden block task.

trial number	type	difficulty	base	length (cm)	color	orientation
1	training	easy	square	9	magenta	
2	training	easy	square	6	dark green	
3	test	medium	hexagon	9	orange	- 45°
4	test	hard	semi-circle	6	cyan	- 45°
5	test	medium	oval	9	violet	+45°
6	test	hard	isosceles trapezoid	6	orange	+45°
7	test	medium	rectangle	9	cyan	- 45°
8	test	hard	isosceles triangle	6	violet	- 45°
9	baseline	very easy	circle	9	yellow	+45°
10	baseline	very easy	circle	6	dark blue	- 45°
11	test	hard	isosceles triangle	9	green	+45°
12	test	medium	rectangle	6	red	+45°
13	test	hard	isosceles trapezoid	9	blue	- 45°
14	test	medium	oval	6	green	- 45°
15	test	hard	semi-circle	9	red	+45°
16	test	medium	hexagon	6	blue	+45°

Table 2

Arrival time (seconds) and percentage of anticipatory trials by velocity, occluder size and age group. The duration of the full occlusion (seconds) is determined by velocity and occluder size.

velocity	occluder size	full occlusion duration	age group	arrival time		anticipatory trials ¹
				<i>M</i>	<i>SD</i>	<i>M</i>
fast	small	1	2	-0.07	0.41	44
			2.5	-0.08	0.26	50
			3	-0.26	0.28	75
	big	1.5	2	-0.31	0.46	62
			2.5	-0.58	0.47	81
			3	-0.85	0.36	94
slow	small	2	2	-0.69	0.67	70
			2.5	-0.90	0.64	88
			3	-1.00	0.39	86
	big	3	2	-1.20	0.75	80
			2.5	-1.13	1.21	69
			3	-1.81	1.14	86

Note. *M* = mean, *SD* = standard deviation.

¹ A trial was defined as anticipatory if at least one raw gaze position (blinks and saccades removed) was on the reappearance AOI during the full occlusion.

Figure Captions

Figure 1. Exemplary stills of the continuous motions presented in the eye-tracking task (panel A); areas of interest (AOIs) that were used to analyze gaze positions in the eye-tracking tasks (panel B); stimuli presented in the wooden blocks tasks, with order indicated by arrows (panel C); example of a trial sequence in the wooden block task (panel D).

Figure 2. Percentage of trials the toddlers looked at a specific area of interest (AOI) in the eye-tracking task, averaged across toddlers. Time windows range from the start of the animation until 1.5 s after the end of the full occlusion. The lines were slightly smoothed with the LOESS function.

Figure 3. Eye-tracking measures by age. (A) Switches from stimulus to pivot AOI during visible rotation. (B) Percentage of time the toddlers looked at the stimulus AOI during visible rotation. (C) Arrival time at the reappearance AOI. (D) Looking back to the disappearance AOI. Columns show results from fast and slow velocity conditions.

Figure 4. Results of the wooden block task. (A) Age-related changes in preadjustment. (B) Percent of the trials solved by time elapsed. Note that at the hard difficulty, age differences were present early on and persisted. (C) Age-related changes in success within 4 s since trial start. (D) Percentage of the trials solved successfully (i.e., within the available 20 s) by age and difficulty level. The lines in (C) and (D) are LOESS curves.

Figure 5. Correlation between arrival time in the eye-tracking task and preadjustment in the wooden block task by age and velocity.

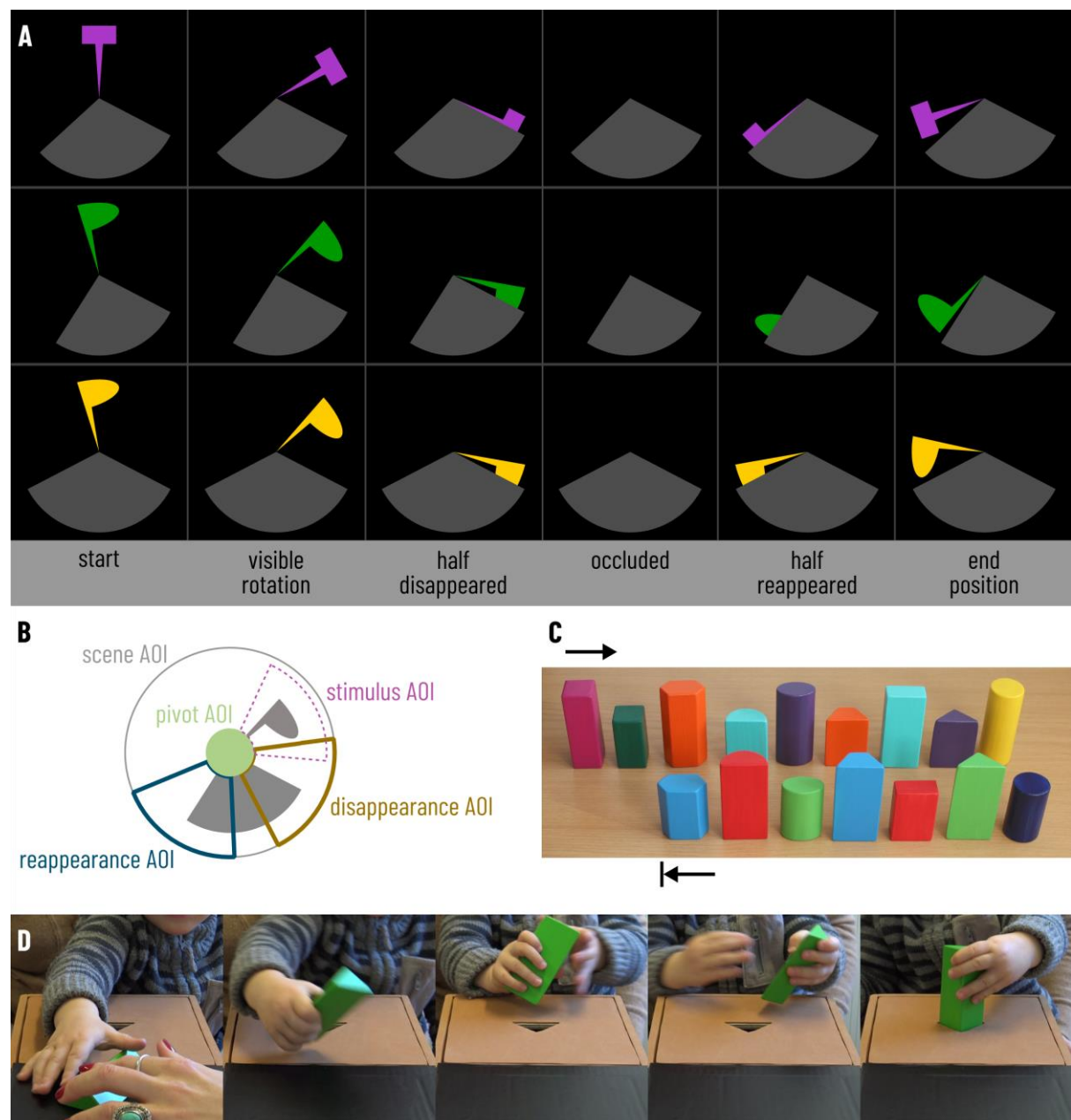


Figure 1

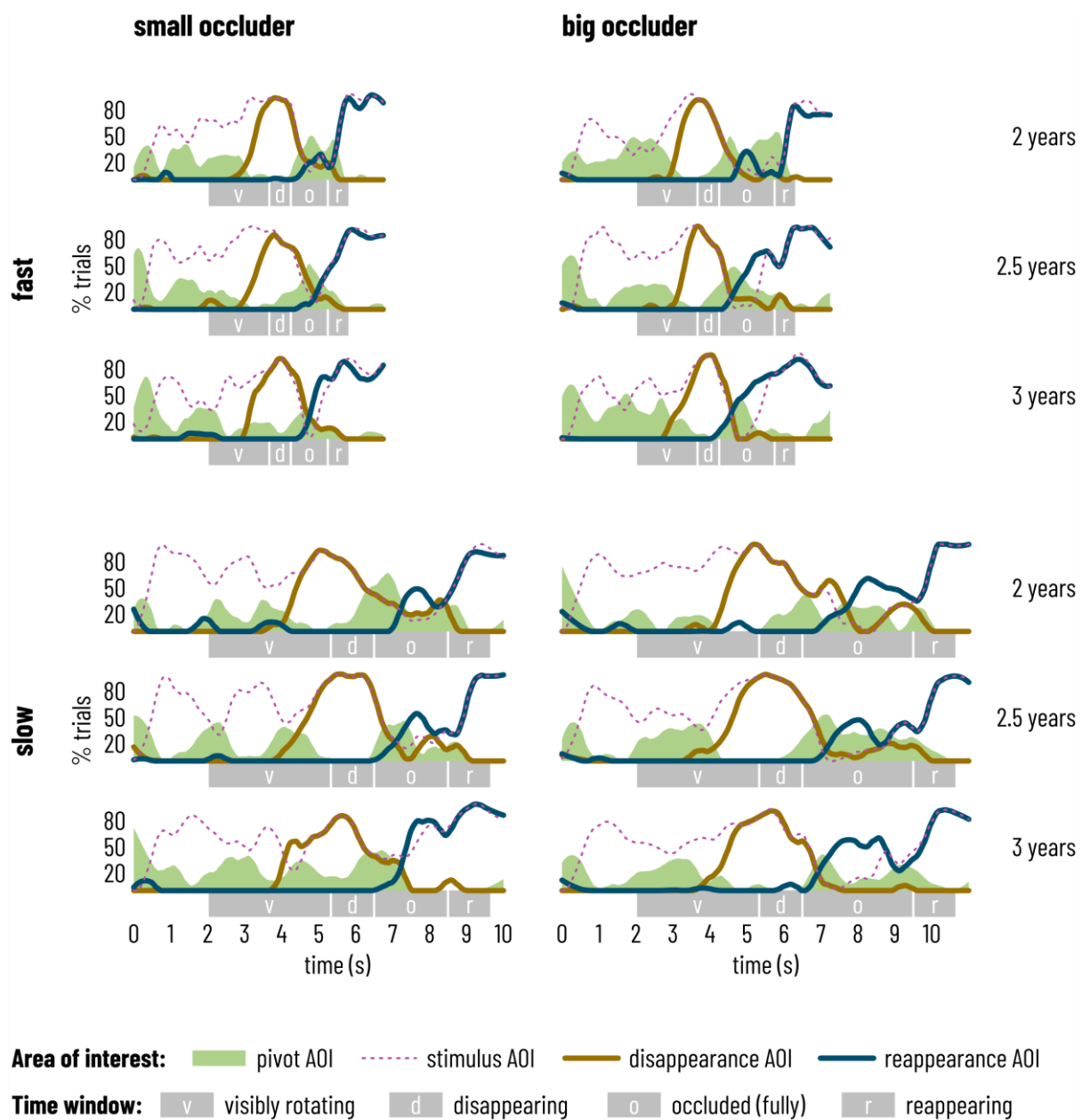


Figure 2

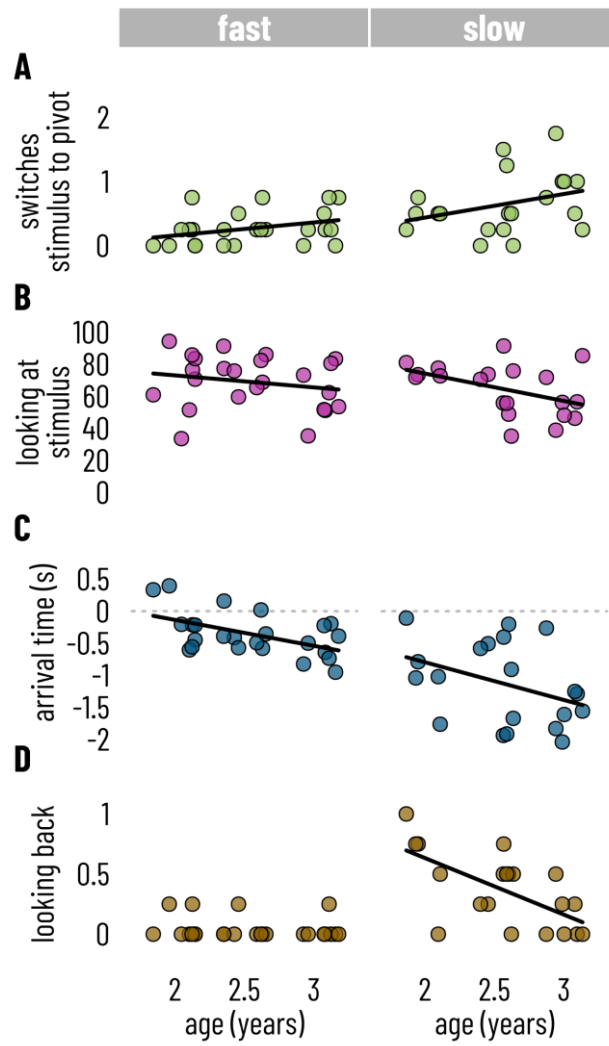


Figure 3

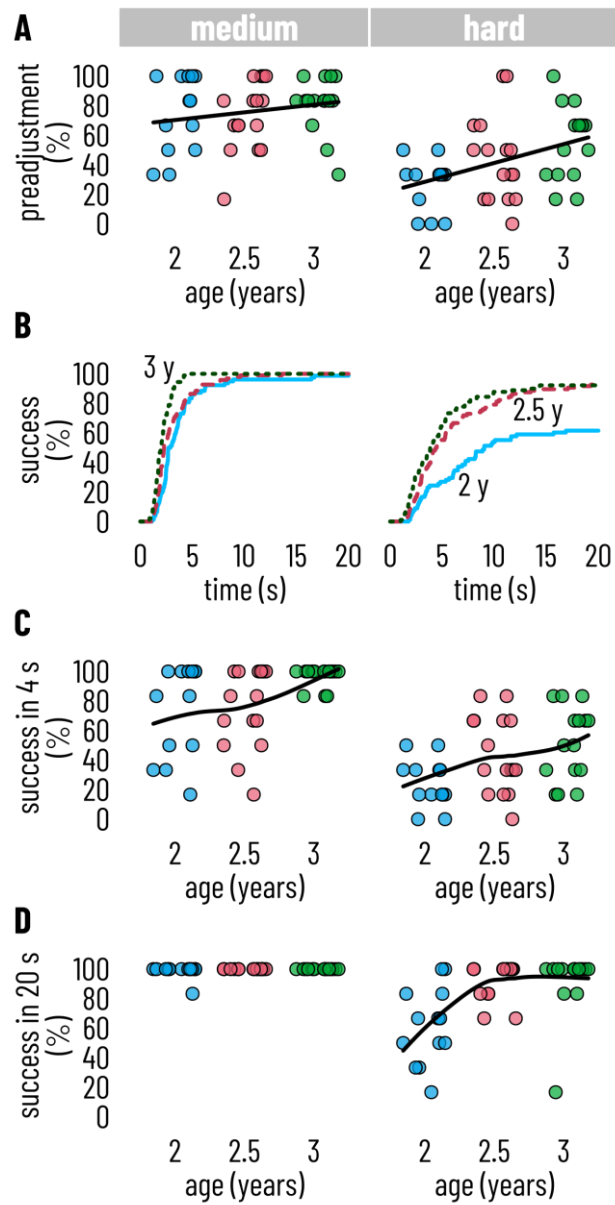


Figure 4

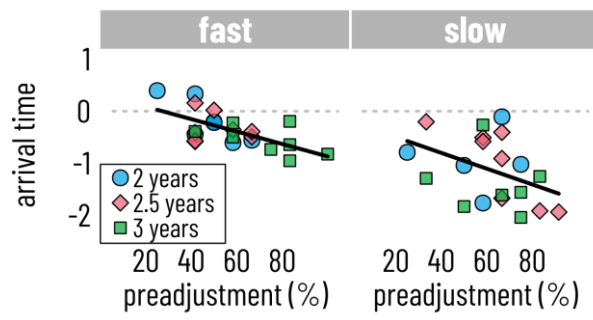


Figure 5

Study 2


Age-related changes in how 3.5- to 5.5-year-olds observe and imagine rotational object motion

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Abstract

Mental representations of rotation were investigated in 3.5- to 5.5-year-old children ($N = 74$) using a multi-method approach. In an eye-tracking task, children were presented with a shape that rotated, disappeared behind an occluder, and reappeared either in its original or mirror-reversed form. In a new behavioral mental-rotation task, children were asked to choose one of two shapes that would fit onto a counterpart. Eye-tracking results indicated that perception of visible rotation changed with age and already the youngest children showed anticipatory eye movements. On the behavioral task, children below age 4 performed above chance up to angles of 150° and performance improved with age. These findings suggest that mental representations of rotation are present below 4 years of age.

Keywords: mental rotation, spatial imagery, cognitive development, looking time, preschoolers

Age-related changes in how 3.5- to 5.5-year-olds observe and imagine rotational object motion

Rotation is a basic type of motion. However, not much is known about how young children learn to perceive and think of rotation. There is first evidence that between approximately 14 and 36 months of age, toddlers increasingly rotate objects prospectively to fit them into apertures (Jung et al., 2015, 2018; Örnkloo & von Hofsten, 2007; Smith et al., 2014; Street et al., 2011). This might indicate that toddlers are increasingly able to mentally rotate simple shapes such as rods, rectangles, or triangles before trying to physically fit them into a hole. However, it is only between 4 and 6 years of age that children begin to be successful on behavioral mental-rotation tasks that require mentally rotating asymmetrical shapes in order to distinguish them from mirror images (for a review, see Frick et al., 2014). On the other hand, some infant studies using looking-time methods have suggested that mental representation of rotational object motion may already be possible in the first year of life (e.g., Hespos & Rochat, 1997; Möhring & Frick, 2013). These conflicting findings may be due to the fact that different paradigms have been used in different age groups. As a result, there is still much uncertainty about how and when young children mentally represent rotation. In the present study, we therefore used an eye-tracking task as well as a behavioral task to test how the perception and mental representation of rotational object motion develops between 3.5 and 5.5 years of age.

To date, few studies have addressed the question of how children perceive rotational motion. Infants have been shown to track a small object that moved on a circular path but stayed upright while doing so (Gredebäck et al., 2005; Grönqvist et al., 2006). Interestingly, from approximately 8 months of age, infants not only followed the moving object, but planned their eye-movements and tracked the object predictively (Gredebäck et al., 2005). Whereas in these studies, the object remained upright while it moved on a circular trajectory,

a recent study tested how children learn to perceive an object that rotates, so that it changes its own orientation (Pedrett et al., 2020). In this study, toddlers observed a shape that looked like a 'p' and rotated clockwise on a computer screen. Eye-tracking data showed that between 2 and 3 years of age, toddlers increasingly combined tracking the outer part of the rotating shape with looks to the pivot point. This might have provided toddlers with information on how the *orientation* of the shape changed, which is a key characteristic of rotation.

Some studies investigated whether infants and toddlers already had an expectation about how the orientation of an object would change with rotation. Rochat and Hespos (1996) presented infants with an upright 'T' that rotated visibly for 120°, then disappeared behind an occluder, and stopped at 180°. After the occluder was removed, infants looked longer when the 'T' was upright than when it was upside-down, suggesting that the infants had mentally extrapolated the movement and anticipated the upended orientation of the 'T' after the rotation. Similar results were also found with other rotation angles (Hespos & Rochat, 1997). At 16 months of age, toddlers have been shown to expect in which direction a duck would face after a completely hidden rotation (Frick & Wang, 2014). Moreover, a recent eye-tracking study showed that toddlers between 2 and 3 years of age looked predictively to where a rotating shape that was briefly occluded would reappear (Pedrett et al., 2020). This suggested that the toddlers either mentally represented the circular trajectory of the outer part of the shape, or that they expected how the orientation of the shape would change during occlusion.

Further evidence for mental representation of the orientation of a line (or the main axis of an object) comes from object-fitting studies. Already at 14 months of age, toddlers were found to bring a cylindrical rod into an upright position before trying to insert it through a circular aperture (Örnkloo & von Hofsten, 2007). Between 18 and 24 months of age, toddlers increasingly preadjusted the longitudinal axis of objects such as cuboids or cars to

insert them into an aperture (Smith et al., 2014). These prospective alignments might indicate a simple type of mental rotation in the sense of imagining how a line or the longitudinal axis of an object would change its orientation during rotation. However, other strategies could also have led to preadjustments. For example, the toddlers could have iteratively rotated the object in the air, comparing the object with the aperture at each step and rotating it further until it was aligned. Thus, it is not clear whether toddlers performed mental rotation, or whether they used other cognitive processes. At 30 months of age, however, preadjustments of a rod started already at the beginning of the transport phase towards an aperture (Jung et al., 2015), so that a simple type of mental rotation seems likely.

Toddlers not only preadjust rods or the main axis of an elongated object. At 24 months of age, toddlers have been found to preadjust a disk before inserting it into a slot (Street et al., 2011). Another object-fitting study showed that when presented with elongated objects, toddlers increasingly also considered additional features than the longitudinal axis (Örnkloo & von Hofsten, 2007). For example, when 26-month-olds were asked to insert a rod with a triangular base into a triangular aperture, they not only brought the rod into an upright orientation, but also frequently rotated the base correctly before trying to insert the rod into the aperture. If mental rotation is the reason for these preadjustments, this would mean that at 26 months of age, toddlers can mentally rotate simple shapes such as an equilateral triangle. A subsequent study showed that between 2 and 3 years of age, toddlers also increasingly preadjusted shapes such as a half-circle before inserting them into apertures (Pedrett et al., 2020). If mental rotation was the underlying mechanism for these preadjustments, this would suggest that the ability to mentally rotate shapes improves tremendously between 2 and 3 years of age.

A more sophisticated kind of mental rotation would be to mentally rotate a highly asymmetrical shape well enough to be able to distinguish it from its mirror image. This level

of sophistication is what is typically tested by classic behavioral mental-rotation tasks. In the original task devised by Shepard and Metzler (1971), participants were presented with 2D-drawings of two abstract 3D-objects, consisting of cubes. The objects differed in orientation, and the participants were asked whether the two objects were the same or mirror versions of each other. The results indicated that participants rotated one of the objects mentally to align it with the other and then checked whether they were the same or not.

One of the first tasks testing mental rotation in children presented drawings of two bears, each with one arm raised (Marmor, 1975). The two bears were presented in different orientations, and the children were asked to decide whether the two bears had the same arm raised. Thus, the task was similar to the original task for adults (Shepard & Metzler, 1971), but the stimuli were more attractive two-dimensional drawings that had to be rotated in the picture plane only. The results showed that 5-year-old children were able to mentally rotate up to 150°. Several later studies found corroborating evidence for mental rotation in 5-year-olds (Foulkes & Hollifield, 1989; Frick et al., 2009; Frick, Ferrara, et al., 2013; Funk et al., 2005; Hahn et al., 2010a, 2010b; Kosslyn et al., 1990). However, mental rotation does not seem to be fully developed at 5 years of age, as high success rates were not consistently found (Dean & Harvey, 1979; Hawes et al., 2015; Krüger & Krist, 2009; Platt & Cohen, 1981).

Before the age of 5 years, results are even more mixed. Marmor (1977) conducted a follow-up study with 4-year-olds (from 4 years 0 months to 4 years 11 months) and found high success rates up to 150°. However, these success rates might have been inflated as Marmor excluded many children based on a prior training with upright pictures. Other studies did not find clear evidence for mental rotation in 4-year-olds (Quaiser-Pohl et al., 2010) or showed success rates that were slightly better than guessing, but mostly at small disparities (Estes, 1998; Wimmer et al., 2016). To adapt a mental-rotation task more to young children,

Frick, Hansen, et al. (2013) presented two ghosts that were mirror versions of each other, and asked children to select the ghost that would fit into a hole. Thus, the children did not need to understand verbal concepts such as 'same', 'different', or 'mirror-reversed'. In this task, 4-year-olds succeeded with rotation angles up to 120°.

Several studies also tested whether children below 4 years of age are capable of mental rotation (Frick, Ferrara, et al., 2013; Frick, Hansen, et al., 2013; Noda, 2010). Results showed that, as a group, children performed near chance, indicating that they were mostly guessing. However, recent evidence suggested that mental rotation could be trained, so that children below 4 years of age performed slightly better than chance after several training sessions (Krüger, 2018).

As of yet, it is not clear what the limiting factors are for young children to succeed on these traditional mental-rotation tasks. Are they not yet capable of mentally rotating highly asymmetrical shapes, or do they struggle with decision making, response inhibition, or understanding task instructions? It has been argued that there might be a dissociation between these explicit tasks of mental rotation and measures tapping more implicit knowledge (Frick et al., 2014). Some studies using looking-time measures have suggested an earlier onset of mental rotation (e.g., Frick & Möhring, 2013; Möhring & Frick, 2013; Moore & Johnson, 2008; Quinn & Liben, 2014; Schwarzer et al., 2012). For example, in a study with 6-month-olds (Möhring & Frick, 2013), a shape that looked like a 'p' or 'q' was moved straight down behind an occluder. When the occluder was lowered, it revealed the original shape or its mirror image in one of five orientations. The infants looked longer when the shape that reappeared was mirror-reversed, suggesting that the infants might have mentally rotated the shape. Yet, this could not be found in toddlers (Pedrett et al., 2020).

In the present study, we thus used a multi-method approach to investigate the perception and mental representation of rotational object motion in children between 3.5 and

5.5 years of age. Each child participated first in an eye-tracking task that assessed looking times as well as gaze positions during the observation of a transiently hidden object rotation. Then the same children participated in a novel behavioral task that presented asymmetrical mirror images and required an explicit choice, but was specifically adapted to the young age of the participants.

In the eye-tracking task, children were presented with a rotating shape that briefly disappeared behind an occluder and reappeared in its original or mirror-reversed form. First, we measured how the children observed the visible rotation. As toddlers have been shown to increasingly combine tracking the outer part of the shape with switches to the pivot point with increasing age (Pedrett et al., 2020), we hypothesized that this develops further between 3.5 and 5.5 years of age. Second, we measured anticipatory eye-movements to the reappearance side of the occluder once the shape had disappeared, which would indicate a mental representation of the circular trajectory of the outer part of the shape or of how the orientation of the shape would change during occlusion. We expected anticipatory eye-movements to develop with age in terms of more frequent and earlier eye-movements to the reappearance side of the occluder. Third, we hypothesized that during the occlusion, children would mentally rotate the shape so well that they could distinguish it from its mirror image, and that therefore, children would be surprised and look longer at the scene if the mirror-reversed rather the original shape reappeared.

The novel behavioral task was designed to measure mental rotation of highly asymmetrical shapes and whether children could distinguish them from mirror images, similar to classic mental-rotation tasks. However, as we aimed to investigate mental rotation at 4 years of age and younger, we adapted the task to this age. Previous tasks presented the shapes not only in different orientations, but also in different locations, so that to mentally superimpose one shape onto the other, mental rotation and additional horizontal or vertical

motion was necessary (e.g., Frick, Hansen, et al., 2013; Kosslyn et al., 1990). We constructed the novel mental-rotation task so that children could mentally superimpose one shape onto the other by means of mental rotation alone. Inspired by the ghost task (Frick, Hansen, et al., 2013), the task also offered an intuitive response format with low working memory demands, in that children could see both options clearly. Moreover, the pivot point and rotation direction were predefined, reducing the degrees of freedom and thus the number of possible decisions. Children were presented with two wooden boards. On each board, there was a cardboard flag that could be physically rotated around its foot, which was attached to a rod in the center of the board. Thus, the pivot point was visible. On each board, a silhouette served as counterpart. The silhouettes were the same on both boards, yet the cardboard flags were mirror versions of each other, so that on one board, the flag could be rotated exactly onto the silhouette, but on the other board, it would not match the silhouette. Children were asked to physically rotate the flag that would fit. By means of mental rotation, participants could figure out which one of the flags would fit before making a choice. It was analyzed how often they chose the correct flag. We expected that this task would likely detect mental rotation below 4 years of age, even without training.

Method

Participants

The full sample consisted of 74 children (39 girls, 35 boys) between 3.5 and 5.5 years of age ($M = 4.5$, $SD = 0.6$). Out of these, 67 children passed the inclusion criteria of the eye-tracking task and 72 those of the behavioral mental-rotation task (see inclusion criteria below). The children were recruited from diverse locations such as day-care centers, courses, parks, or the maternity unit of a general hospital, and some parents volunteered via the lab website. When the child was in the right age, the family was contacted by phone. The children spoke German or French and were tested in their preferred language. Many children

spoke more than one language. The children were predominantly from middle-class families and lived near or in a small city in Switzerland. Prior to the study, parents gave informed, written consent. After the study, the children received a certificate and a small gift, such as stickers or a toy. The study followed ethical guidelines and was approved by the Internal Review Board of the university. For some statistical analyses of the novel behavioral mental-rotation task, the sample was split into four age groups: 3.75 (3.5 – 4 years, $n = 18$), 4.25 (4 – 4.5 years, $n = 19$), 4.75 (4.5 – 5 years, $n = 17$), and 5.25 (5 – 5.5 years, $n = 18$). These age groups were chosen before data collection.

Eye-tracking task

Apparatus

The eye-tracking task was performed in a dimly lit room at the university. In this room, an area (170 x 170 cm) was enclosed by a black curtain and contained a comfortable chair for the participants, a computer screen, an eye-tracking camera, and a video camera. The children sat either on their parent's lap or on the chair. In the latter case, the parents were standing behind, outside of the children's viewing range. The children had a distance of approximately 60 cm from the computer screen (ASUS, ROG Swift PG278Q, 27", 2560x1440, 60 Hz). The parents were instructed not to talk to their child during trials.

The experimenter controlled the experiment from behind the curtain, using Matlab software (R2012a) with Psychtoolbox 3.0.9 (Brainard, 1997) and Eyelink Toolbox, which ran on a PC with a Windows 7 operating system. An *Eyelink 1000 Remote* Eye-Tracker (SR Research) recorded the child's eye movements with a sampling rate of 500 Hz. A small sticker that was attached to the child's forehead provided information about the child's head position, so that the eye-tracker could compute gaze position regardless of head movements. The infrared eye-tracking camera with its 890-nm-illuminator was below the screen and thus also had a distance of approximately 60 cm to the child. To detect saccades (rapid, abrupt eye

movements) and blinks, Eyelink's standard settings were used (i.e., saccade velocity threshold = $30^\circ/\text{s}$, saccade acceleration threshold = $8000^\circ/\text{s}^2$, saccade motion threshold = 0.1° , blink offset verify time = 12 ms). A video camera with infrared function (Sony, DCR-AX33) was positioned next to the eye-tracking camera and was linked to a control monitor, allowing the experimenter to observe the child during the experiment.

Procedure

As soon as the child and the parent had entered the room, a cheerful movie scene started playing on the participant screen. The child was invited to sit down in front of the screen and was offered a small cracker. The sticker for the eye-tracking was attached to the child's forehead. The experimenter adjusted the eye-tracking camera and settings. For the calibration, animated stars that changed in color and size appeared in succession at five different locations on the screen together with a sound. After the calibration, the child saw a static flower image in the center of the screen.

Then the experiment began and 6 trials (2 familiarization and 4 test trials) were presented, which all followed the same structure. First, an attention getter directed the child's attention towards the center of the screen. Attention getters differed from trial to trial, but all consisted of a small image that moved slightly, accompanied by sound. As soon as the child looked at the attention getter, the experimenter started a computer animation featuring a rotating shape. The animation began with a short and cheerful sound and ended with a short beep sound.

Familiarization trials. In the first familiarization trial, the computer animation showed a magenta shape on a black background (Figure 1, row 1). The shape looked like a 'T', but the stem tapered towards the lower end. The lower end was the pivot point for the rotation and was located at the center of the screen. The 'T' had a height of 9 cm and covered an angle of 35° . Thus, when it rotated 35° around its foot, it changed its location

completely. At the start of the animation, the 'T' had an orientation of -90° (i.e., 9 o'clock). It stayed there for 2 seconds and then rotated clockwise with a constant velocity of $60^\circ/\text{s}$ until it had reached an orientation of 117.5° (ca. 4 o'clock). The 'T' remained visible at 117.5° until the end of the trial.

The second familiarization trial was similar to the first, but part of the trajectory of the rotating shape was hidden by a gray occluder, which was shaped like a piece of pie (Figure 1, row 2). The occluder had a radius of 10 cm and covered an area from 0 to 95° . Thus, when the rotating shape had an orientation of -17.5° , it began to be partially occluded, and at 17.5° , it was fully occluded. The full occlusion lasted 1 s. The shape started to reappear at 77.5° and was fully visible again at 112.5° . After having fully reappeared, the shape rotated 5° further, creating a small gap to the occluder. At this end position of 117.5° , the shape remained visible until the end of the trial.

Test trials. Each child was presented with 4 test trials (Figure 1, rows 3-6). The test trials followed the same structure as the second familiarization trial, but asymmetrical flags roughly resembling letters such as 'P' or 'F' were used as the rotating shapes. Four different flags were used, all covering an angle of 35° . They all had a vertical stem that tapered towards the lower end, but differed in what their top part looked like (see Figure 1). For each of the 4 flags, a mirror version was created. In the following, a flag with its top part pointing toward the right will be referred to as "p-like", and a flag with its top part pointing toward the left as "q-like".

The 4 test trials each featured a different shape in a different color. Shape and color were presented in the same order to all children (see Figure 1). The 4 test trials also varied in whether the *shape before the occlusion* was p-like or q-like, and whether the *shape after the occlusion* was the same as the shape before the occlusion (congruent) or its mirror image (incongruent). For measurement of looking times, it was important to counterbalance possible

effects due to the order of congruent and incongruent trials. Therefore, 8 trial orders were randomly assigned to participants (while making sure that they were distributed roughly equally across age and sex). At the end of the four test trials, cheerful music started playing, and the experimenter thanked the child for the participation. The child could then watch a short scene from a movie.

Measuring looking times. Based on previous findings (Pedrett et al., 2020) that looking times that were coded manually from videos correlated strongly with looking times obtained through eye-tracking ($r = .95$), looking times were measured with the eye-tracker in the present study. The eye-tracker transmitted the raw gaze positions to Matlab in real-time for each frame of the animation (60 Hz, the frame rate of the participant screen). An area of interest (AOI) was defined: a circle in the center of the screen, with a radius of 13 cm. If the child's gaze was within this scene AOI, it was coded as "looking at the scene". If not, this was defined as "looking away". In all trials, measurement of looking times began when the rotating shape had an angle of 77.5° , as this was the last time the rotating shape was still fully occluded on trials with occluder. If the child did not look at the scene AOI for at least 200 ms within the next 1.5 s, the trial was terminated at the end of this critical time window. If the child looked at the scene AOI for at least 200 ms during this time window, the trial ended as soon as the child looked away for one consecutive second or when a timeout (5 s in familiarization trials; 20 s in test trials) was reached, whichever came first.

Data preprocessing

In addition to the scene AOI, smaller AOIs were created to analyze more closely where the children looked during specific parts of the events. All of these particular AOIs were within the scene AOI. These AOIs were named *pivot AOI*, *disappearance AOI*, *reappearance AOI*, and *stimulus AOI* (Figure 2) and constructed based on the same rules as in a previous eye-tracking study with toddlers (Pedrett et al., 2020). The pivot AOI was a circle

with a radius of 3 cm in the center of the screen. Thus, the center of the pivot AOI was at the same location as the pivot point of the rotating shape. The radius of 3 cm was a conservative choice to ensure that looking at the pivot point with a measurement error of up to 3 cm could not be misinterpreted as looking to any of the following AOIs. The disappearance AOI was shaped like a piece of pie and covered the disappearance side of the occluder, starting at -35° and ending at 35° , thus having a width that was twice the stimulus width. The radius was 13 cm and thus 3 cm larger than the radius of the occluder. The pivot AOI was subtracted from this AOI, so that the disappearance AOI covered only those parts of the disappearance side of the occluder that had at least 3 cm distance from the pivot point. The reappearance AOI had the same shape, but covered the reappearance side of the occluder, starting at 60° and ending at 130° . The stimulus AOI was special, in that it rotated together with the stimulus. Again, in order to account for some measurement error, it covered a 70° angle (thus twice the stimulus width), and the radius was 12 cm (3 cm larger than the height of the stimulus). The pivot AOI was also subtracted from the stimulus AOI. Since the stimulus AOI rotated, it could overlap with the disappearance or the reappearance AOI.

Inclusion criteria. An algorithm checked each trial with regard to the following inclusion criteria, which were identical to those used by Pedrett et al. (2020): (1) *The child had encoded the stimulus*: In a time window from the start of the trial until the start of full occlusion, the child's gaze was on the stimulus AOI for at least 1 s. (2) *The child had seen the rotation*: In a time window from the start of rotation until the start of full occlusion, the child looked at the stimulus or pivot AOI for at least 33% of the time. (3) *The child was attentive directly before the occlusion*: In a time window of 1 s before the beginning of the full occlusion, the child looked at least 200 ms at the stimulus, pivot, or disappearance AOI. (4) *The child was attentive after the occlusion*: Within 1.5 s after the end of the full occlusion, the child looked at least 200 ms at the stimulus, pivot, or reappearance AOI. The time

window for this criterion was 0.5 s longer than for criterion 3 in order to give children (who might have still been looking at the disappearance AOI when the stimulus started reappearing) enough time to switch their gaze to the stimulus, pivot, or reappearance AOI. A child's data was included if at least 3 out of the 4 test trials passed the inclusion criteria. This was the case for 67 out of 74 children (= 91%).

Calibration accuracy. For the 67 included children, the average calibration error was 0.83 visual degrees. (Please note that this is the angle between the eye of the child and two points on the screen, not to be confused with stimulus orientation). The eye-tracker also reported calibration error in screen pixels, which were converted into cm. The average horizontal error was 0.64 cm ($SD = 0.24$), and the average vertical error was 0.66 cm ($SD = 0.25$). Age neither correlated with the horizontal error ($r = -.02$, $p = .89$) nor with the vertical error ($r = .07$, $p = .58$). With respect to the size of the AOIs, this calibration error can be considered small.

Behavioral task

Stimuli

The stimuli were five colorful cardboard flags, similar to the flags used in the eye-tracking task. The five flags differed in color and shape (see Figures 3 and 4), and for each, a mirror version was created. The backs and sides were black. The flags were 3 mm thick. The vertical stem was 9 cm long and a wire loop was attached to the bottom end of the stem. The angle between the left side of the flag, the center of the wire loop (which served as the pivot point of the rotation), and the right side of the flag was approximately 30°.

Each flag-pair was presented on a pair of wooden boards. Each board was a square (28 x 28 x 0.3 cm) and was covered with black adhesive foil. The two boards were positioned next to each other, one left and one right of the child's line of sight, with a 4-cm gap in between. Each board had a vertical rod in its center (2 cm long, 0.8 cm in diameter, dark-

silver), to which the flags could be attached with their wire loop and rotated on the surface of the board. On each board, a silhouette of a flag was cut out of the black adhesive foil, revealing the beige wood underneath. The beige silhouettes on the two boards were identical, so that they both either matched the p-like or the q-like flag. The silhouettes were displayed either at 3 o'clock (i.e., 90° clockwise deviation from upright) on both boards or at 9 o'clock (i.e., a 90° counterclockwise deviation from upright) on both boards.

Procedure

Each child was tested individually in a bright laboratory room at the university. Each child was tested individually. Most children were seated on a chair in front of a table (both child size), with the parent seated diagonally behind the child. A few children sat on the parent's lap. Two experimenters were present: one experimenter sat to the right of the child and presented the stimuli; another experimenter sat on the floor and handled an occluder. The session was filmed by two video cameras: one camera (Sony, DCR-AX33) was opposite to the child, approximately 10 cm higher than the table, and filmed the stimuli as well as the child; the second camera was approximately one meter higher than the table and captured the stimuli on the table from an elevated side-view. The parents were instructed not to interfere during trials, but they could encourage the children between trials.

The task consisted of an instruction, a test block (8 trials), a short break, an abbreviated instruction, and a second test block (8 trials). All children received the same order of trials, as we were primarily interested in testing how task performance develops with age and whether it correlated with performance in the eye-tracking task. The rotation direction was clockwise in the first instruction and test block, and counterclockwise in the second instruction and test block.

Instruction for Test Block 1. The task began with a board-pair on the table, with silhouettes at 3 o'clock, matching the q-like version of the violet flag (see Figure 3). The

experimenter pointed out that the two silhouettes on the boards were the same. Then, the experimenter presented the matching flag, holding it in the air, and explained that the surface was colored and that the back side was black. To demonstrate how the flag could be rotated, the experimenter placed the flag on one of the two boards at approximately 10 o'clock by hooking the flag's wire loop to the rod and rotated the flag slowly *clockwise* until it fully covered the silhouette (at 3 o'clock). The experimenter commented that the flag fit exactly. To finish the presentation, the experimenter rotated the flag approximately 35° backwards (counterclockwise), resulting in a small gap (approximately 5°) between the flag and the beige silhouette (Figure 3).

Then, the experimenter introduced the non-matching flag, held it onto the first flag, and explained that the two flags were different. To demonstrate the rotation, the experimenter placed the non-matching flag onto the second board, rotated it onto the silhouette, commented that it did not fit, and then rotated it 35° backwards. Now, both flags were on the boards at a disparity of 35° to the silhouettes (so that the gap between a flag and a silhouette was 5°), as depicted in Figure 3. The experimenter explained that the task was to rotate one of the flags, but only the one that matched the silhouette. As a warm-up, the child was then asked to rotate the flag that would fit onto the silhouette. If the child chose the correct flag, the experimenter praised the child. If the child hesitated or chose the wrong one, the experimenter pointed out the correct solution and then, either the child or the experimenter rotated the correct flag.

For the first instruction trial, the second experimenter positioned a thin occluder on the table, so that the child could not see the stimulus material. The main experimenter switched the two flags behind the occluder, so that the matching flag was now on the other board, again at 35° disparity. The main experimenter asked the child to rotate the shape that fits, and when the child seemed ready, the second experimenter removed the occluder. The

child could then rotate one of the flags and received feedback as in the warm-up trial. The second instruction trial was similar, but the flags were again switched behind the occluder before the trial began, so that they were positioned as in the warm-up trial.

The instruction was repeated in abbreviated form with another board-pair, now with silhouettes matching the p-like flag. The experimenter demonstrated how the flags could be rotated onto the silhouettes and let the children complete one warm-up and two instruction trials.

Test Block 1. Immediately after the instruction, 8 test trials were presented. At the start of each trial, the main experimenter placed a board-pair (still with silhouettes at 3 o'clock) onto the table and let the child have a short look at the boards. The second experimenter then positioned the occluder. Hidden from the child's view, the main experimenter placed the two flags onto the boards, at counterclockwise angular disparities of 90, 120, 150, or 180° from the silhouettes. A *clockwise* rotation was thus the shortest way to rotate a flag onto the silhouette in most cases and was hence considered the default rotation direction. The experimenter asked the child: "Now you can rotate the shape that fits. Are you ready?" When the child was ready, the second experimenter removed the occluder, and the child made a choice. If the child chose the correct flag, the main experimenter praised the child; else, the experimenter pointed out the correct solution, and either the child or the experimenter rotated the correct flag. At the end of each trial, the experimenter removed the flags and boards.

The test trials varied regarding the presented *flag-pair*, *disparity*, *silhouettes*, and *correct side* (see Figure 4, rows 1 and 2). Flag-pairs were presented in the order 'cyan-green-orange-magenta' in test trials 1-4, and the reverse order in the test trials 5-8. Disparity was presented in rising order (90, 90, 120, 120, 150, 150, 180, 180° for the test trials 1-8, respectively). The silhouettes could either both match the p-like or the q-like flag

and were presented in the order 'p-q-p-q' in trials 1-4, and in reverse order in the trials 5-8. The correct side (i.e., the board with the flag that matched the silhouette) was *left* or *right*, and was presented in the order of 'right-left-left-right' in test trials 1-4, and 'left-right-right-left' in test trials 5-8.

Instruction for Test Block 2. The children took a short break outside of the laboratory before completing the second block. In this block, the silhouettes were always presented at 9 o'clock, and a *counterclockwise rotation* was demonstrated in the instruction and the shortest way to move most flags onto the silhouettes. The instruction began with a board-pair with silhouettes that matched the p-like version of the violet flag-pair. The experimenter demonstrated how the flags could be rotated onto the silhouettes, let the child do one warm-up and one instruction trial, and then removed the board-pair. This was repeated with the board-pair with silhouettes that matched the q-like flag.

Test Block 2. The subsequent test trials are shown in Rows 3 and 4 in Figure 4. Flag-pairs, disparities, and silhouettes were presented in the same orders as in the first block. However, unlike in Block 1, the order of correct sides was: 'left-right-right-left' for test trials 1-4, and 'right-left-left-right' for test trials 5-8.

Inclusion criteria

Inclusion criteria were that children completed all trials and complied with task instructions. Data of 72 (out of 74) children conformed to these criteria and were included in statistical analyses. One child (from age group 3.75) did not complete the task, and another child (from age group 4.75) did not comply with task instructions but often chose both flags at the same time.

Results

Eye-tracking task

Results of the eye-tracking task will be presented in chronological order, first reporting eye-tracking data of how the children observed the visible rotation before the occlusion, then analyses of how predictively children looked to the reappearance side of the occluder once the shape had disappeared, and finally tests of whether the children looked longer at the scene if the shape that reappeared was incongruent with the shape before the occlusion than when it was congruent. The 67 children observed the animations attentively and on average looked at the scene AOI in 91% ($SD = 5$) of the time before the full occlusion started. The remaining 9% consisted of saccades, blinks, looking away, or other kinds of data loss.

Observing the visible rotation

During the fully visible rotation before the occlusion, the children tracked the stimulus with smooth pursuit eye movements, but also performed saccadic eye-movements. Gaze was most of the time on the stimulus AOI (73%) and second most on the pivot AOI (14%). With increasing age, the children looked less long at the stimulus AOI (Pearson's $r = -.27, p = .026$) and had a non-significant tendency to look longer at the pivot AOI (Pearson's $r = .23, p = .059$). We also analyzed how often the children switched between the stimulus AOI and the pivot AOI with at least one saccade in between. Even though switches from the stimulus to the pivot AOI were rather rare ($M = 0.13$ times per trial, $SD = 0.19$), their frequency increased with age (Spearman's $\rho = .27, p = .026$). Switches in the other direction were more common ($M = 0.40$ times per trial, $SD = .30$), and their frequency did not change with age (Spearman correlation: $p = .36$). There were no sex differences in any of these four dependent variables (all $|ts| < 0.96$, all $ps > .34$). In summary, the children looked

less at the stimulus AOI and switched more often from the stimulus to the pivot AOI with increasing age.

Predictive eye-movements

Whether the children formed an expectation of where the rotating shape would reappear was tested by measuring how predictively the children looked at the reappearance side of the occluder once the shape had disappeared. In 5 out of the 253 included trials, gaze was already at the reappearance AOI at the beginning of the full occlusion. In all other trials, gaze arrived at the reappearance AOI either during the full occlusion or within 1076 ms after the end of the full occlusion. Arrival time at the reappearance side of the occluder was defined so that zero indicated the end of the full occlusion, and negative values indicated predictive eye-movements. Arrival times of all 253 individual trials showed a bimodal distribution, with a peak 600-900 ms before the full occlusion ended and another peak 200-300 ms after the occlusion ended. This showed that in most individual trials, children looked either clearly predictively or clearly reactively to the reappearance AOI. After calculating the mean for each child, arrival time had a more unimodal distribution. Mean arrival time at the reappearance AOI was -251 ms ($SD = 300$). This was significantly earlier than the end of the full occlusion, as a one-sample t -test showed, $t(66) = -6.86, p < .001, d = 0.84$. Arrival times depended neither on sex ($t = 1.08, p = .28$) nor on age (Pearson's $r = .11, p = .40$); already the youngest children anticipated where the shape would reappear.

Looking times

To test whether children mentally rotated the shape well enough to notice whether the shape that reappeared was congruent or incongruent with the shape before the occlusion, we analyzed how long the children looked at the scene AOI after the full occlusion with a repeated-measures ANCOVA. Whether the reappearing shape was congruent versus incongruent with the one before the occlusion was the within-participant variable, sex was

entered as a between-participant variable, and age was entered as a continuous, mean-centered covariate. The results showed that the children did not distinguish between congruent and incongruent shapes ($F < 1$), and there were no other main effects or interactions (all F s < 1.74 , all p s $> .19$).

Behavioral task

In the behavioral mental-rotation task, a trial was defined as successful if the child chose the correct flag by physically rotating it onto the silhouette. If the child first touched the wrong flag or rotated it less than 20° towards the silhouette before choosing the correct flag, this was also considered correct. If the child responded by only pointing at a flag or only touching a flag, the trial was considered correct if the child chose the correct flag at first try. To compute inter-rater reliability, data from 60% of the children were also coded by a second rater. The two raters agreed on whether the trial was successful or not in 99.4% of the trials.

Success rates of the 72 children are shown in Figure 5. To determine whether the children performed better than chance, success rates of each age group were analyzed with a one-sample t -test, using 50% correct as chance-level. The 5.25-year-old children solved 90% ($SD = 10$) of the trials correctly, which was significantly above chance, $t(17) = 17.30$, $p < .001$, $d = 4.08$. The 4.75-year-olds also showed high success rates and chose the correct flag in 88% ($SD = 12$) of the trials, which was significantly above chance, $t(16) = 13.22$, $p < .001$, $d = 3.21$. The 4.25-year-olds were successful in 82% ($SD = 13$) of the trials, $t(18) = 10.84$, $p < .001$, $d = 2.49$, and even the 3.75-year-olds performed significantly above chance, with a success rate of 72% ($SD = 18$), $t(17) = 5.10$, $p < .001$, $d = 1.20$. An ANCOVA on success rates was calculated, with age (mean-centered covariate) and sex as independent variables. Success rates increased significantly with age, $F(1, 68) = 23.32$, $p < .001$, $\eta^2_p = .26$. There was no sex difference and no interaction of sex and age (both F s < 1).

Table 1 shows success rates for each disparity separately. Testing these success rates against chance revealed that the oldest three age groups performed significantly above chance at all disparities. The 3.75-year-olds were significantly better than could be expected by chance at the disparities of 90°, 120°, and even 150°, but not at 180° (see also Figure 6). The results remained the same with Bonferroni correction for multiple testing.

Correlations between performance measures in the two tasks

Even though on a group-level, children's looking times did not depend on whether the shape that reappeared was congruent or incongruent with the shape before the occlusion, individual differences in looking times could nevertheless be related to success in the behavioral mental-rotation task. To test whether performance in the two tasks was related, and possibly measured the same underlying cognitive process, Pearson correlations between looking-time differences (looking time to the congruent minus the incongruent shape) and success rates in the behavioral task were analyzed. The correlation was not significant ($r = -.05$, $p = .69$), and neither was a partial correlation that controlled for age ($r = -.04$, $p = .78$).

To test whether predictive eye-movements to the reappearance side of the occluder (eye-tracking task) correlated with looking times (eye-tracking task) as well as with success in the behavioral mental-rotation task, Pearson correlations were performed. The results showed that predictive eye-movements, as measured by arrival time at the reappearance side of the occluder, did not correlate with looking-time differences between congruent and incongruent shapes ($r = -.20$, $p = .11$; $r = -.20$, $p = .12$ if controlled for age). Neither did predictive eye-movements correlate with success in the behavioral mental-rotation task ($r = -.004$, $p = .98$; $r = -.10$, $p = .42$ if controlled for age).

Discussion

To investigate how mental representations of rotational motion develop, children between 3.5 and 5.5 years of age were tested in an eye-tracking task and in a novel behavioral mental-rotation task. Results showed that in the eye-tracking task, children observed the visibly rotating shape differently with increasing age. The older they were, the more often they combined tracking the outer part of the stimulus with also attending the pivot point. During occlusion, children of all ages showed predictive eye-movements and looked at the reappearance side of the occluder before the shape reappeared. Looking times, however, did not provide evidence for children's differentiation of whether the shape that reappeared was the congruent or incongruent shape. Thus, this task yielded evidence that the children formed an expectation that the shape would reappear beyond the occluder, but not about how exactly the shape would look after the occlusion. In the behavioral task, on the other hand, the same children were able to distinguish shapes of similar complexity from mirror images. Thus, children between 3.5 and 4 years of age showed evidence for successful mental rotation of up to 150°, and children between 4 and 5.5 years up to 180°.

Observing the visible rotation

The eye-tracking data showed developmental changes in how the children encoded the visible rotation. With increasing age, the children increasingly combined looking at the outer part of the shape with switches to the pivot point, confirming our first hypothesis. This visual exploration may have informed children on how the orientation of the shape changed during the rotation. Along with previous findings (Pedrett et al., 2020), this suggests that perception of visible rotation develops between 2 and 5.5 years of age and thus overlaps with development of mental rotation abilities (Frick et al., 2014). Future studies might test how children below 2 years of age perceive rotation, and at which age children start to switch between tracking the motion of the shape and looking at the pivot point. In the present study,

the duration of visible rotation before the occlusion was relatively short; future studies might investigate eye movements during longer periods of visible rotation in order to get more detailed results.

Predictive eye-movements

Negative arrival times in the eye-tracking task indicated that the children looked predictively to the reappearance side of the occluder after the object had disappeared. This suggests that children performed a mental prediction of how the outer part of the shape moved on a circular trajectory or how the orientation of the shape changed with rotation. These predictive eye-movements have previously been shown to develop significantly between 2 and 3 years of age (Pedrett et al., 2020). However, contrary to our second hypothesis, no increase in anticipatory eye-movements was found across the age range of 3.5 to 5.5 years in the present study, suggesting that this development levels out after 3.5 years of age.

Noticeably, the children looked predictively to the reappearance side of the occluder even though they had not received instructions to do so. This suggests that the predictive eye-movements occurred spontaneously. For translational motion, in which the orientation of the object does not change, spontaneous predictive eye-movements across an occluder have been shown already in preverbal infants (e.g., Bertenthal et al., 2012; Gredebäck et al., 2002). Our results extend these findings by showing that young children look predictively even for rotational movement.

Mental rotation in the eye-tracking task

Based on previous studies investigating mental rotation in infants using a violation-of-expectation paradigm, in our third hypothesis, we assumed that children would look longer at the scene if the shape that reappeared was incongruent rather than congruent with the shape before the occlusion. However, children looked roughly equally at either shape, providing no

evidence for mirror-image discrimination. These results are in line with findings in 2- to 3-year-olds (Pedrett et al., 2020) but contrast findings in infants (Frick & Möhring, 2013; Möhring & Frick, 2013). Several possibilities could explain the different results. For one, it is possible that the children in the present study actually did rotate the shape mentally and noticed that the incongruent rather than the congruent shape reappeared, but that this ability was not reflected in looking times at this age. It is possible that children kept looking at the screen because they did not want to miss future events, whereas infants might be less inclined to uphold visual attention when nothing happens on the screen. This might have masked effects of children's surprise about the reappearance of a different shape. Or it is possible that at this age, children have become more used to things not behaving according to physical laws on screens. Alternatively, it is possible that children did not encode the shape well enough before the occlusion to form a clear expectation of how the shape would look after the occlusion. Hence, no conclusion can be drawn about children's mental-rotation abilities, based on these non-significant looking-time results.

Mental rotation in the behavioral task

The novel behavioral mental-rotation task was similar to the looking-time part in the eye-tracking task, in that it tested whether children were able to mentally rotate asymmetrical shapes well enough to distinguish them from mirror images. However, the novel behavioral task required an explicit response. Children at the ages of 5.25, 4.75, and even 4.25 years demonstrated mental rotation up to a disparity of 180°, and children at the age of 3.75 years (3.5 – 4) still showed evidence for mental rotation up to 150°. This shows that mental rotation of asymmetrical shapes is possible below 4 years of age and extends previous findings, according to which children below 4 years of age performed near chance level on slightly more demanding tasks (Frick, Ferrara, et al., 2013; Frick, Hansen, et al., 2013; Noda, 2010). Previous studies typically presented the shapes not only in different orientations, but also in

different locations, and thus measured not only mental rotation, but a combination of mental rotation and horizontal or vertical motion. It is possible that as children grow older, they are increasingly able to combine mental imagery of rotation with other types of motion.

Even though the present task offered an intuitive, visible response format with low working-memory load, the task still posed high demands on attentional control, inhibition, and decision making, as evidenced by children's (informally observed) behavior when solving the task: To encode the stimuli, children often looked back and forth between the flags and the silhouettes, reflecting a rather advanced control of visual attention. Moreover, children sometimes touched the wrong flag, then inhibited this response, looked at the other flag, and corrected their choice. While physically rotating the correct flag, children sometimes looked at the other flag, likely to double-check whether their choice was correct.

Despite these task demands, children between 3.5 and 4 years of age were successful with rotation angles of up to 150° in this novel mental-rotation task. Future studies will show whether children below 3.5 years of age would be successful with smaller rotation angles, simpler shapes, and further adaptations of task demands and instructions. This may also shed light on the question of whether mental rotation was involved in object-fitting tasks (c.f., Jung et al., 2015, 2018; Örnkloo & von Hofsten, 2007; Pedrett et al., 2020; Smith et al., 2014; Street et al., 2011).

Correlations between tasks

There were no correlations between looking-time differences in the eye-tracking task, predictive eye-movements in the eye-tracking task, and success in the behavioral task. As looking-times did not yield any evidence for children's differentiation of mirror-images, it could be that children either did not mentally rotate the shapes during the eye-tracking task well enough to notice when the incongruent shape reappeared, or it could also be that children used mental rotation but that looking-times were no valid measure for this in the

tested age range. In both cases, no correlation with another performance measure for mental rotation could be expected.

A possible explanation for the result that predictive eye-movements in the eye-tracking task were not correlated to success in the behavioral task is that these two measures tapped different cognitive processes, with different developmental trajectories. Predictive eye-movements have been shown to develop drastically between 2 and 3 years of age (Pedrett et al., 2020), but no further development was found between 3.5 and 5.5 years of age in the present study. In contrast, success in the behavioral mental-rotation task increased markedly in the present study. In addition, it is also possible to differentiate these two performance measures on a theoretical level, as for predictive eye-movements, it may be sufficient to mentally represent the circular trajectory of the non-central part of the shape or how the orientation of the main axis of the shape changes during rotation. Thus, predictive eye-movements may reflect a similar mental process as preadjustments of simple shapes in object-fitting tasks (Jung et al., 2015, 2018; Örnkloo & von Hofsten, 2007; Smith et al., 2014; Street et al., 2011). This notion was corroborated by recent findings of significant correlations between predictive eye-movements and preadjustments in an object-fitting task (Pedrett et al., 2020). The novel behavioral mental-rotation task in the present study, in contrast, requires children to mentally rotate the shapes so well that they can distinguish them from mirror images. Hence, the novel mental-rotation task likely captures mental rotation on a higher level of sophistication, similar to what is being measured in classic 2D-mental-rotation tasks for older children and adults (e.g., Frick et al., 2009; Hahn et al., 2010a; Kosslyn et al., 1990; Marmor, 1975; Quaiser-Pohl et al., 2010).

Conclusion

In conclusion, the present findings showed that imagery and perception of rotational motion develop significantly between 3.5 and 5.5 years of age. In the newly developed

behavioral mental rotation task, children below 4 years of age were able to mentally rotate an asymmetrical shape up to 150° , shedding new light on the development of mental representations. This novel task could be solved by imagining only rotational motion, without additional horizontal or vertical motion, suggesting that in previous studies, children below 4 years of age might have had difficulties combining mental rotation with other (e.g. lateral) mental transformations. Future studies may test this possibility more directly.

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Table 1

Success rates in the behavioral mental rotation task by age group and disparity. Each row in the table corresponds to a one-sample t-test that compared success rates against chance, with 50% correct as chance-level.

age group	<i>n</i>	disparity	<i>M</i>	<i>SD</i>	<i>t</i>	df	<i>p</i>	Cohen's <i>d</i>
5.25	18	90	97	8	24.78	17	<.001***	5.84
		120	88	15	10.29	17	<.001***	2.43
		150	92	15	11.90	17	<.001***	2.81
		180	85	17	8.44	17	<.001***	1.99
4.75	17	90	91	15	11.20	16	<.001***	2.72
		120	88	16	10.10	16	<.001***	2.45
		150	87	18	8.45	16	<.001***	2.05
		180	84	22	6.47	16	<.001***	1.57
4.25	19	90	89	13	13.57	18	<.001***	3.11
		120	79	22	5.62	18	<.001***	1.29
		150	82	16	8.43	18	<.001***	1.93
		180	78	20	5.95	18	<.001***	1.37
3.75	18	90	81	18	7.08	17	<.001***	1.67
		120	74	22	4.59	17	<.001***	1.08
		150	75	26	4.12	17	<.001***	0.97
		180	60	31	1.33	17	.20	0.31

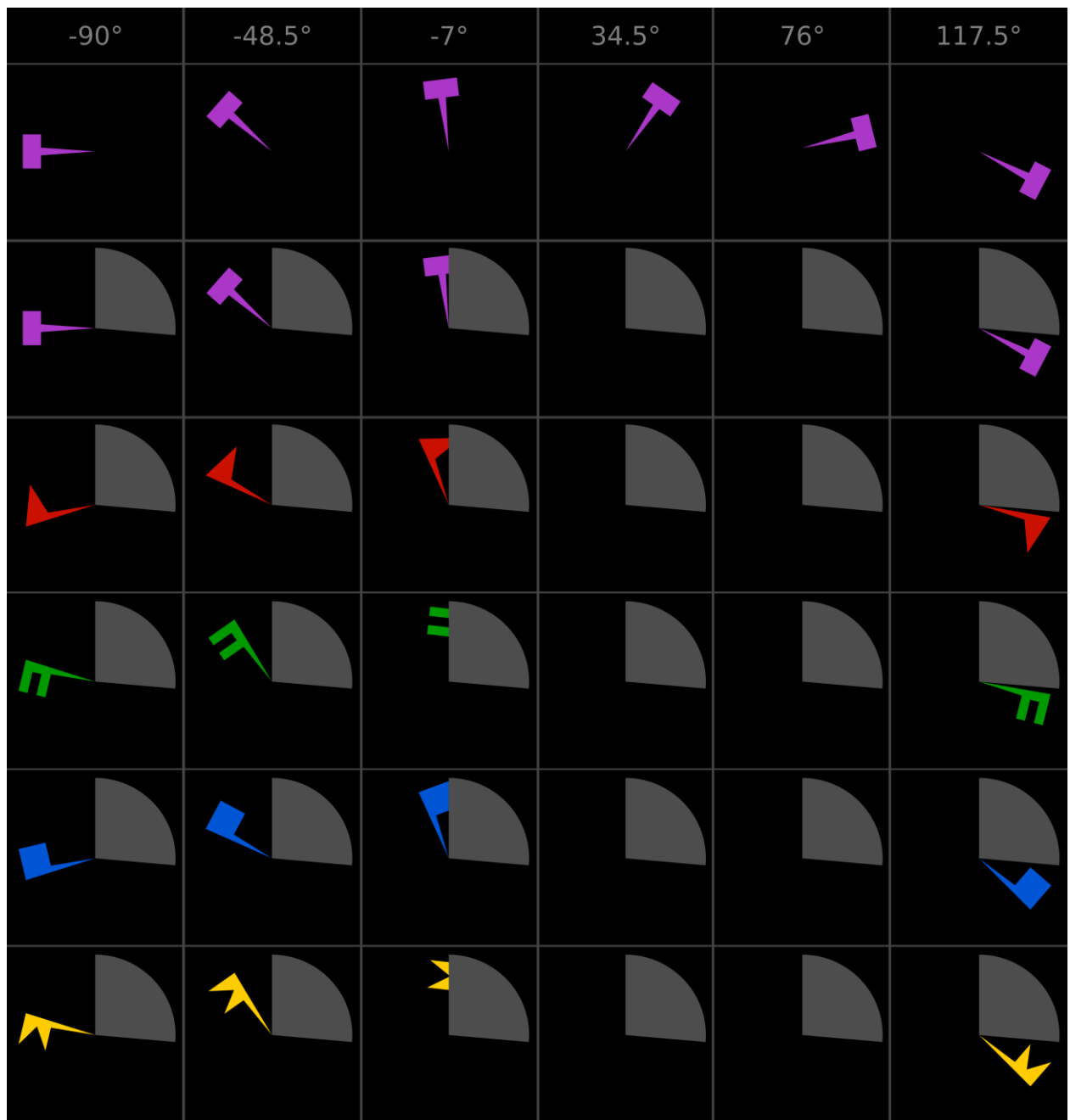


Figure 1

The 2 familiarization trials and 4 test trials in the looking-time paradigm. For test trials, an example order of the shape before the occlusion (p-like versus q-like) and the shape after the occlusion (congruent versus incongruent) is displayed.

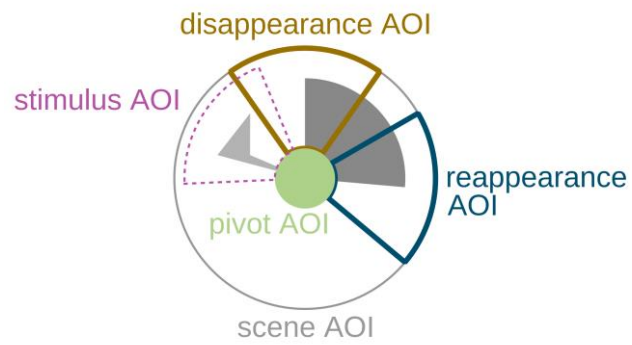


Figure 2

The areas of interest (AOIs) in the looking-time paradigm.

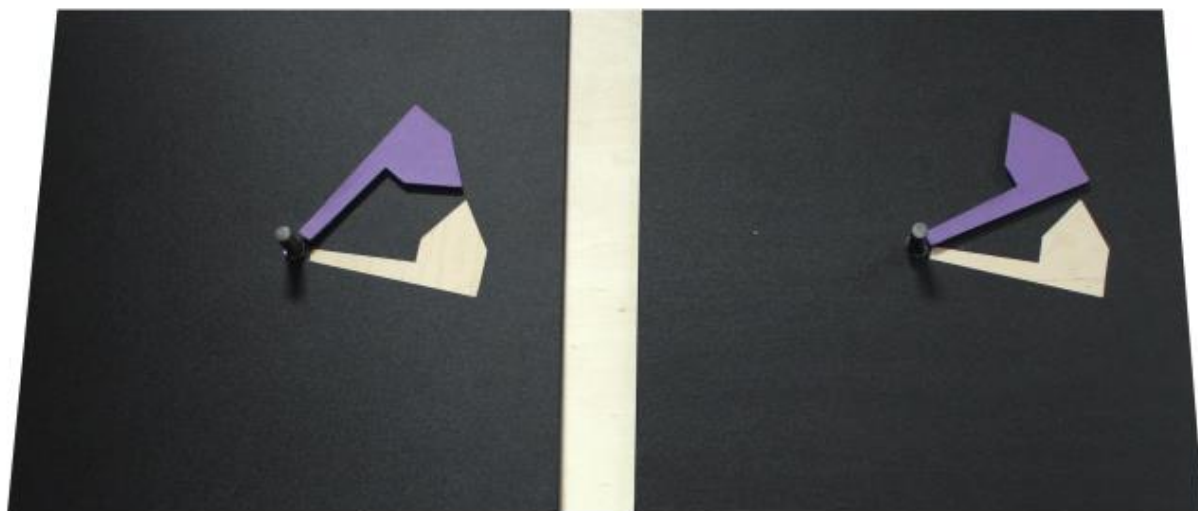


Figure 3

An example of an instruction trial in the behavioral mental-rotation task.

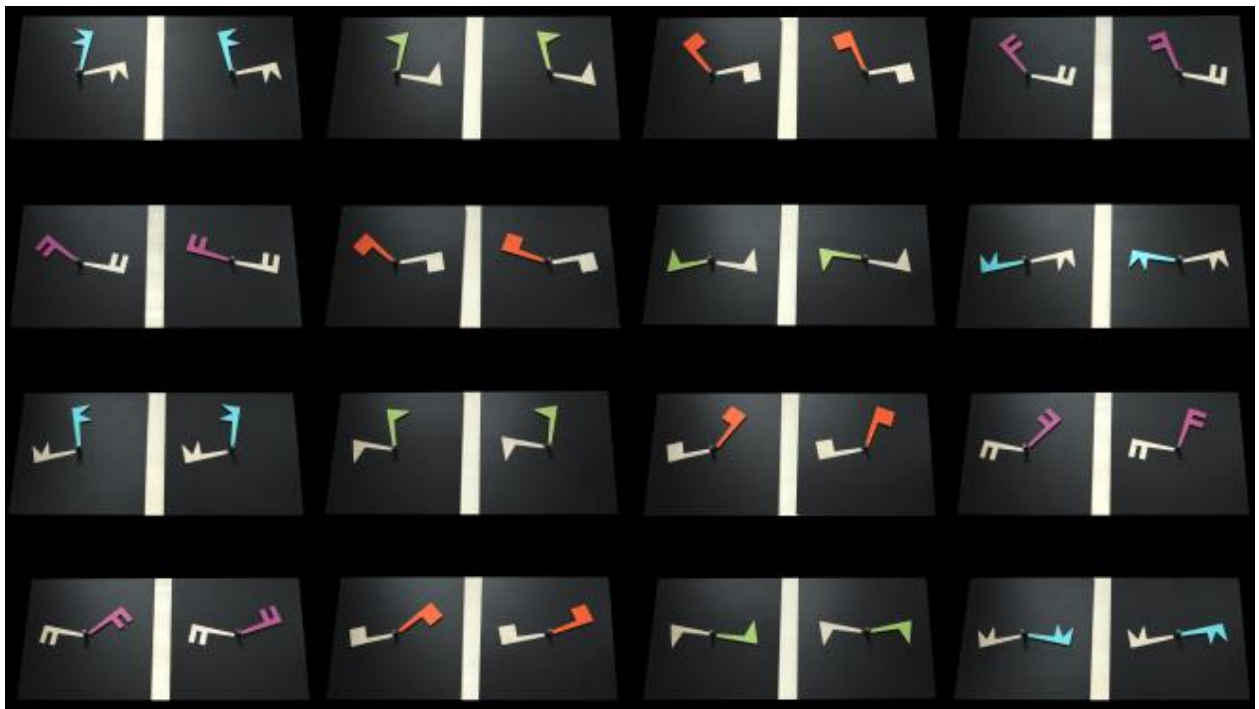


Figure 4

All 16 test trials in the behavioral mental-rotation task.

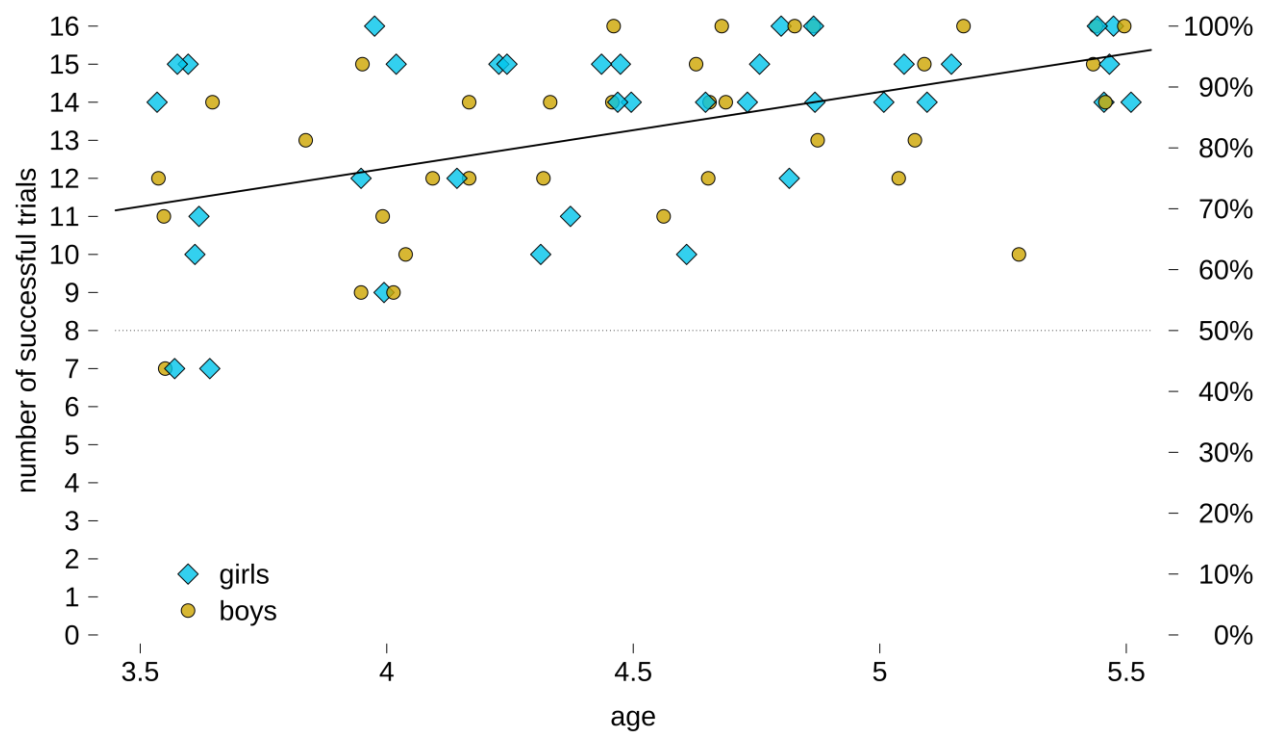
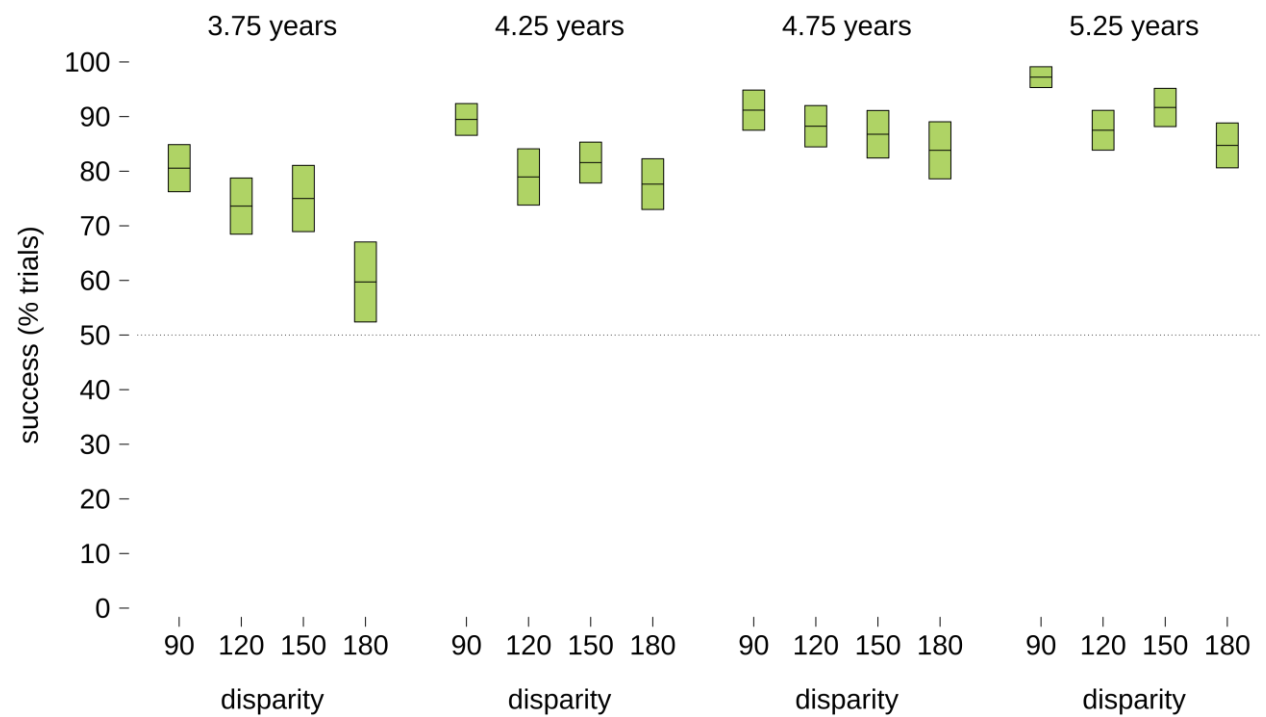


Figure 5

Success rates in the behavioral mental-rotation task by age and sex. Chance-level is success in 8 trials (=50%).

**Figure 6**

Success in the behavioral mental-rotation task by age group and disparity. The rectangular plot symbols cover the mean plus and minus one standard error of the mean. Chance-level is success in 50% of the trials.

Study 3


Children between 3 and 3.5 years of age can perform mental rotation of asymmetrical shapes

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Abstract

In this study, young children's ability to mentally rotate asymmetrical shapes was examined. Thirty children between 3 and 3.5 years of age (15 girls, 15 boys) solved a mental-rotation task, which presented a clearly defined rotation axis and was adapted to this young age by means of intensive demonstration and motivating feedback. As in traditional tasks used with adults, asymmetrical shapes were presented, which had to be differentiated from their mirror images in different orientations, thereby impeding alternative strategies. The results revealed that the children performed above chance and showed mental rotation of up to 120°. A few children demonstrated mental rotation of up to 150 or 180°. In conclusion, the present study provided behavioral evidence for mental rotation below 3.5 years of age.

Keywords: mental rotation, spatial imagery, cognitive development

Children between 3 and 3.5 years of age can perform mental rotation of asymmetrical shapes

Mental rotation - the ability to represent and change the orientation of an object in one's mind - is not only one of the most investigated spatial skills in adults, it also has important translational implications for academic achievement, as it has been associated with later mathematics performance (e.g. Frick, 2019) and successful careers in science, technology, engineering, and math disciplines (Shea et al., 2001; Wai et al., 2009). Nevertheless, the early development of this ability is still unclear, due to a lack of tasks that are suitable for young children. Studies using touchscreen or puzzle-game-like tasks showed that children started to perform above chance level between 4 and 6 years of age (Frick et al., 2014). However, even on these child-friendly tasks, younger children seemed to struggle. In contrast, object-fitting studies have revealed that between 1 and 3 years of age, toddlers increasingly rotate an object before inserting it into an aperture (Jung et al., 2015; Örnkloo & von Hofsten, 2007; Smith et al., 2014; Street et al., 2011). These preadjustments in motor planning might be based on a mental rotation process. It is hence conceivable that children below age four are able to rotate an object mentally, but struggle with other task requirements, such as understanding instructions or making forced-choice decisions (for an overview, see Frick et al., 2014). Indeed, a recent study (Pedrett et al., submitted) provided initial evidence that children as young as 3.5 to 4 years of age are successful on a very intuitive mental-rotation task that minimized requirements. The goal of the present study was to investigate whether children below age 3.5 can perform mental rotations when solving a task that is further adapted to this young age group.

In the original mental-rotation task for adults (Shepard & Metzler, 1971), participants were presented with two asymmetrical objects that differed in orientation. The participants were asked whether the asymmetrical objects were exactly the same, or whether they were

mirror versions of each other. Shepard and Metzler (1971) concluded from their results that adults used mental rotation to mentally align the two objects and thus compare them. Using similar tasks, several subsequent studies have found converging evidence for mental rotation in children as young as 5 years. For example, Marmor (1975) presented children with 2D-drawings of two bears that had one arm raised. The bears were depicted in different orientations, and the children were asked to decide whether the two bears were the same or different (i.e., had the same or different arms raised). The results of this study suggested that 5-year-olds were able to use mental rotation. Several other studies confirmed mental rotation of two-dimensional stimuli at the age of 5 years (Estes, 1998; Foulkes & Hollifield, 1989; Frick et al., 2009; Frick, Ferrara, et al., 2013; Frick, Hansen, et al., 2013; Funk et al., 2005; Hahn et al., 2010a, 2010b; Kosslyn et al., 1990; Krüger & Krist, 2009; Noda, 2010; Quaiser-Pohl et al., 2010). However, Platt and Cohen (1981) as well as Dean and Harvey (1979) did not find high success rates in 5-year-olds, suggesting that mental rotation is not yet fully developed at this age. Moreover, in a study by Hawes et al. (2015), most 5-year-olds had difficulties mentally rotating abstract 3D-objects.

Before the age of 5 years, evidence of mental rotation is even more mixed. Marmor (1975) not only discovered mental rotation in 5-year-olds, but also tested 4-year-olds in a follow-up study (Marmor, 1977). She found evidence for mental rotation in children between age 4 years 0 months and 4 years 11 months, but she included only those children in her analysis who had high success rates at a disparity of 0°. Estes (1998) presented 4- and 6-year-olds with two drawings of monkeys differing in orientation, and asked them whether the monkeys held up the same or different arms. The 4-year-olds were successful in 60% of the trials, which was barely but significantly above chance. However, this success rate was averaged across all trials, including some with small disparities that did not necessarily require mental rotation (less than 90°). Similar results were found by Wimmer et al. (2016).

Lately, researchers have devised new methods in order to adapt mental-rotation tasks to be used with younger children. Instead of asking children whether two shapes were different or not, Frick, Ferrara, et al. (2013) used a touchscreen to present children with an L-shaped figure varying in orientation, and a ground with two L-shaped holes that were mirror versions of each other. The task was to point to the hole which the shape would fit into. Thus, both choices (i.e., the two holes) were clearly visible, so that children did not need to understand and remember abstract response options such as *same* or *different*. Children between 4 years 6 months and 5 years 6 months performed well with disparities of up to 135° and response times increased with increasing disparity. Children between 3 years 6 months and 4 years 5 months, in contrast, performed near chance at all disparities. Thus, these simplifications did not allow very young children to succeed. In another puzzle-like task, Frick, Hansen, et al. (2013) presented children with two ghosts – which were mirror versions of each other – and asked the children to choose the ghost that would fit into a hole that differed in orientation. In this task, children between age 4 years 4 months and 4 years 8 months showed high success rates for disparities of up to approximately 120°, whereas children between age 3 years 5 months and 3 years 8 months performed near chance level. Similarly, Noda (2010) did not find evidence for mental rotation at age 3 years 10 months. However, some recent studies suggest that mental rotation can be trained in 3-year-olds with enough repetitions or a design that presents trials in an order of increasing difficulty. For example, in a training study (Krüger, 2018), 3-year-olds participated in two training sessions (with a total of 117 trials) and reached success rates of approximately 60% at all disparities in a third test session. Three-year-olds also showed high success rates in a study by Fernández-Méndez et al. (2018), in which the *ghost* stimuli from Frick, Hansen, et al. (2013) were presented in an order of increasing disparity over several sessions. Taken together, these

studies indicated that children typically start to be successful on mental-rotation tasks between 4 and 6 years of age, but that mental rotation might be trained in 3-year-olds.

In an effort to develop a more sensitive measure for mental rotation in young children, a novel mental-rotation task was recently constructed, suitable for children between 3.5 and 5.5 years of age (Pedrett et al., submitted). This task was inspired by the classical task by Cooper and Shepard (1973) that presented asymmetrical 2D-stimuli, but the instructions were adapted to the participants' young age. Two boards were presented side-by-side on a table. Each board supported a cardboard flag that was hooked to a rod in its center, so that the flag could be rotated on the board. Each board also featured an asymmetrical cutout. These cutouts were exactly the same on the two boards, whereas the cardboard flags were mirror versions of each other. Hence, the flag on one board could be rotated onto the cutout, so that it fit perfectly – the flag on the other board would not match the cutout. By means of mental rotation, it was possible to know prospectively which flag would fit. Thus, to measure mental rotation, children were asked to physically rotate only the flag that would fit, and it was analyzed whether they chose the correct one. Children between 4 and 5.5 years of age showed above-chance success rates at disparities of up to 180°. Children between 3.5 and 4 years of age were successful at disparities of up to 150°, with success rates of 81% at 90°, 74% at 120°, 75% at 150°, and 60% at 180°, indicating that children below 4 years of age can perform mental rotation even without training.

A key difference between this novel task (Pedrett et al., submitted) and previous tasks for preschoolers (e.g., Frick, Hansen, et al., 2013; Kosslyn et al., 1990; Quaiser-Pohl et al., 2010) is that in previous tasks, the shapes were presented not only in different orientations, but also in different locations. Therefore, children had to imagine a rotational as well as an additional translational (vertical or horizontal) motion to mentally superimpose the shapes. In the novel task, in contrast, the shape could be transposed onto the cutout by rotary motion

alone. Furthermore, the pivot point and the rotation direction were clearly defined, reducing the degree of freedom of the movement and thus presumably making it easier to anticipate. In line with affordance theory (Jones, 2003), the novel task may have also offered a clear inherent action possibility of how the flag could be rotated around the pivot point, making it easier for children to understand the task.

The aim of the present study was to investigate whether even younger children – between 3 and 3.5 years of age – can mentally rotate asymmetrical shapes and distinguish them from their mirror images. For this purpose, we redesigned the task used by Pedrett et al. (submitted) to better suit this young age group, by changing the instruction, adding more extensive demonstrations, and providing more motivating feedback. We also made task difficulty adaptive, by presenting stimuli at increasing angular disparities from 30 to 120° to all children, and only children with high success rates proceeded to an additional block with larger disparities of 150 and 180°. Assuming that 3-year-olds can perform mental rotation and that this newly designed task allows them to demonstrate this competency, we hypothesized that success rates would be significantly above chance level of 50% correct.

Method

Participants

The sample consisted of 30 children (15 girls, 15 boys) between 3 and 3.5 years of age ($M = 39$ months, $SD = 45$ days). Mean ages of girls and boys differed by zero days. The children were recruited in day-care centers, courses, parks, through the website of the lab, or in a maternity ward of a general hospital. The families were contacted by telephone when the child was at the right age. The mostly middle-class families lived in or near a small city in Switzerland. The children spoke French or German and were tested in their preferred language. Many children spoke more than one language. The parents gave informed, written consent prior to the study. At the end of the study, the children received a certificate and a

small gift, such as soap bubbles or stickers. The study followed ethical guidelines and was approved by the Internal Review Board of the university.

Material

The stimuli were cardboard flags that consisted of a vertical stem and an area at the top right. They roughly resembled letters such as an 'F' or 'P' (see Figures 1 and 2). Five different flags were used. They varied in the shape of the top-right part and in color (violet, cyan, green, orange, magenta). For each of these original flags, a mirror-reversed version was created, so that the top part protruded to the left. This resulted in 5 pairs of flags. The flags had a height of 9 cm and were made of 3-mm-thick cardboard, with colored paper on the surface and black adhesive foil on the back side. The sides were black. A wire loop was attached to the bottom of the vertical stem. The angle between the left side of a flag, the center of the wire loop, and the right side was approximately 30° , so that a flag would change its position completely with every 30° of rotation around the center of the wire loop.

Each flag-pair was presented on a pair of square wooden boards (28 x 28 x 0.3 cm) that were covered in black adhesive foil. The two boards were mounted side-by-side on a wooden panel, with a 4 cm wide gap in between, where the wooden color of the supporting panel was visible. Each of the two black boards had a metal-colored, 2 cm long vertical rod in its center, to which a flag could be attached by means of the wire loop. Each board also showed the cutout of one of the flags, which was created by cutting out the black adhesive foil in the shape of the flag, revealing the beige wood of the board. The cutouts were identical on both boards, so that one flag of a flag-pair would fit exactly onto the cutout, whereas the other flag would not match. The cutouts were either both at 3 o'clock or both at 9 o'clock.

Procedure

Each child was tested individually in a laboratory room at the university. The experimenter explained the study to the parent, while the child had the opportunity to play

and get accustomed to the novel environment. When the child was ready, the main experimenter presented a shape-sorter game as a warm-up, which is easy to solve at this age. After a short break, the child was invited to sit in front of a rectangular table on a chair or on the parent's lap. If the child did not sit on the parent's lap, the parent was behind the child, outside of the child's view. A video camera (SONY DCR-AX3) filmed the child and the stimulus material from the opposite side of the table. An additional camera (SONY DCR-SX15E) filmed the stimulus material from an elevated view at the right side of the table (from the child's point of view). The main experimenter sat at the left side of the table, whereas a second experimenter handled an occluder from the right. The parents were instructed not to help or interact with their children during trials, but they were allowed to encourage and play with them between trials to keep them engaged.

The task consisted of two blocks with a short break in-between. Each block began with an instruction and comprised 8 test trials that presented flags at increasing disparities (Figure 2). All children saw the trials in the same order (see Table 1). Trials varied in rotation direction, disparity, cutouts (whether the cutouts matched the original or mirror-reversed flag of the flag pair), flag pair, and whether the correct response was on the left or right board. Children who solved 12 or more trials correctly in the first two blocks with angles up to 120° were asked whether they wanted to participate in a third block, which presented even larger disparities of 150° and 180° .

Instruction

The first block tested mental rotation in a clockwise rotation direction. Therefore, the instruction trials presented the board-pairs with the cutouts at 3 o'clock and the flags were placed counter-clockwise to them, so that they could be mentally rotated clockwise onto the cutout. The instruction began with a board-pair featuring cutouts that matched the mirror-reversed version of the violet flag (see Figure 1). The experimenter explained that the two

cutouts were identical. Then, the experimenter showed both flags to the child and explained that they were violet on the surface and black on the back side. The experimenter placed the matching flag onto one of the boards, approximately 120° counter-clockwise to the cutout, and demonstrated how the flag could be physically rotated onto the cutout. The experimenter pointed out that the flag matched the cutout exactly, and then rotated the flag 30° counter-clockwise, so that the flag no longer covered the cutout. Next, the experimenter took the second flag, explained that this flag was different from the first, placed it on the other board, and demonstrated how this flag could be physically rotated. When the flag had arrived on the cutout, the experimenter explained that the flag did not fit. Then, the experimenter rotated the second flag 30° counter-clockwise, such that, at the end of this demonstration, both flags were adjacent to the cutouts, as depicted in Figure 1. At this point, the experimenter explained that the task was to turn the flag that fits – and *only* the one that fits – and demonstrated this by moving the correct flag onto the cutout.

To start the first instruction trial, the second experimenter positioned a thin occluder on the table, so that the child could not see the stimulus material anymore. Hidden from the child's view, the main experimenter switched the two flags and again placed them 30° counter-clockwise to the cutouts. The experimenter then asked the child to turn the flag that fits. When the child was ready, the second experimenter removed the occluder, and the child could choose a flag by physically rotating or pointing at it. If the child chose the matching flag, the experimenter praised the child. In case of an incorrect choice, the experimenter encouraged the child to rotate the other flag as well, and then praised the child (if the child hesitated to rotate the other flag, the experimenter rotated it, so that the child could see what the correct solution looked like). The second instruction trial was identical, but before the start of the trial, the two flags were switched, so that the correct flag was now on the other board. After these first two instruction trials, the experimenter changed the board-pair, so that

now the cutouts matched the original version of the violet flag, and repeated the instruction in abbreviated form. Again, the experimenter explained that the two cutouts were identical, demonstrated with both flags how they could be rotated onto the cutouts, and then rotated the flags 30° backwards. The experimenter again explained the task and moved the correct flag onto the cutout. As with the previous board-pair, two instruction trials followed, in which the child was asked to physically turn the matching flag.

The second block was instructed like the first block, but in abbreviated form with only one instead of two instruction trials per board-pair. As the second block tested counter-clockwise mental rotation, it presented board-pairs with the cutouts at 9 o'clock, and the flags were placed clockwise to them, so that a counter-clockwise mental rotation was necessary to align them. The third block began after a short break without further instruction.

Test trials

All test trials followed the same general procedure. A board-pair was placed visibly on the table; then, the occluder was placed in front of it. Hidden from the child's view, the experimenter positioned one flag of a flag-pair on the left board and one flag on the right board, both at the same disparity from the cutout (see Table 1). Next, the experimenter asked the child to rotate the matching flag, and the second experimenter removed the occluder. To respond, the child could physically rotate a flag or point to it. If the child selected the matching flag, the child was praised. If the child selected the wrong flag, the child was invited to rotate the other flag and was then praised; if the child hesitated to rotate the other flag, the experimenter rotated it, so that each child was provided with the same information of what the correct solution looked like.

Results

Data preparation

A trial was defined as solved correctly if the child rotated the correct flag or rotated the incorrect flag slightly (less than 20°) towards the cutout before rotating the correct flag. If the child only touched a flag or pointed at it, the response was considered correct if the child chose the correct flag at first try. Data from 20 children were coded by a second, independent rater. The two raters agreed in 98.6% of the trials on whether they were solved correctly or not.

In the first and second block (with disparities up to 120°), a total of 480 trials was possible (30 children x 16 trials). Out of these, 24 trials were not completed because 3 children did not participate in the second block, and 12 trials were excluded because it could not be determined whether they were correct or not (e.g., the child rotated both flags at the same time). Thus, 444 trials could be analyzed. For statistical analyses of overall success rates, data were averaged across both blocks, so that data from all children could be included. For detailed analyses of specific rotation angles, data were also averaged across both blocks. Thus, analyses of 30° , 60° , and 120° disparities included data of all children, as they all had at least one valid trial per disparity. One child had no valid 90° trial, so that statistical tests for this disparity were based on trials from 29 children. Block 3 presented four 150° and four 180° trials, which were completed by 11 children, yielding a total of 88 trials. Two trials were excluded due to experimenter error, so that 86 trials were analyzed.

Disparities 30, 60, 90, and 120°

Overall, children chose the correct flag in 67% ($SD = 20$) of the trials. A one-sample t -test showed that this was significantly above chance probability of 50%, $t(29) = 4.68$, $p < .001$, $d = 0.85$. Next, success rates were analyzed per disparity, as trials with small disparities (i.e., 30° or 60°) might not have required mental rotation. Success rates for each disparity are

displayed in Figure 3. At a disparity of 30° , children solved 66% ($SD = 30$) of the trials correctly. This was significantly above chance, $t(29) = 2.85$, $p = .008$, $d = 0.52$. At a disparity of 60° , children showed a success rate of 76% ($SD = 21$), which was also better than chance, $t(29) = 6.66$, $p < .001$, $d = 1.22$. Even in trials with a disparity of 90° , children performed significantly above chance level, with a mean success rate of 66% ($SD = 31$), $t(28) = 2.86$, $p = .008$, $d = 0.53$. Success rates were still above chance at a disparity of 120° , with a mean success rate of 62% ($SD = 27$), $t(29) = 2.55$, $p = .016$, $d = 0.47$.

Possible effects of sex, age and disparity on success rates were investigated using an ANCOVA, with disparity as within-participant variable, sex as a between-participants variable and age as a mean-centered covariate. Results showed no main effects of sex, $F < 1$, age, $F(1,25) = 1.69$, $p = .21$, $\eta^2_p = .06$, nor disparity, $F(3,75) = 1.94$, $p = .13$, $\eta^2_p = .07$, but a significant interaction of age and disparity, $F(3,75) = 3.83$, $p = .013$, $\eta^2_p = .133$. No other interactions were found (all F s < 1). To better understand the interaction of age and disparity, separate linear regressions with success as dependent variable and age as predictor were performed for each disparity. At 30° , success did not increase with age, $b = 11.03$, $p = .81$, but older children were significantly more successful at a disparity of 60° , $b = 99.49$, $p < .001$, and tended to be more successful at a disparity of 90° , $b = 89.55$, $p = .053$. At a disparity of 120° , success did not increase with age, $b = -7.20$, $p = .86$.

Additional block with disparities of 150° and 180°

Twelve children (= 40%) solved at least 12 out of 16 trials correctly in blocks 1 and 2 with disparities between 30° and 120° . Out of these, 11 children participated in the additional block with disparities of 150° and 180° , with success in 64% of the trials ($SD = 31$) at 150° and success in 66% of the trials ($SD = 28$) at 180° . Given that only 11 children participated in this block and there were only 4 trials per disparity, both disparities were analyzed together in

order to have sufficient power. Results showed that the overall success rate ($M = 65\%$, $SD = 22$) was significantly above chance, $t(10) = 2.26$, $p = .047$, $d = 0.68$.

Discussion

In the present study, we used a novel task to investigate whether children between 3 and 3.5 years of age can perform mental rotation. The results revealed that success rates were significantly above chance at disparities of 30 to 120°, providing evidence for mental rotation in children between 3 and 3.5 years of age. Some children were even successful with disparities of up to 150 and 180°.

In the present study, disparities were presented in rising order (within blocks). Up to a disparity of 60°, trials could likely be solved without mental rotation, for instance by comparing whether both flags pointed in the same direction (Quaiser-Pohl et al., 2010). Since 60°-trials were performed after the 30°-trials, the higher success rates at 60 than at 30° could be due to practice effects. Yet, success rates at 90 and 120° were smaller than at 60°, even though children had more practice. This corroborates the notion that a simple visual comparison of the two stimuli was no longer possible for these larger disparities, and children first had to align the stimuli mentally. Nevertheless, children still performed above chance level at these and even higher disparities, suggesting that young 3-year-olds can perform mental rotation even without extensive training.

The present results are in line with and extend findings from object-fitting studies (Jung et al., 2015; Örnkloo & von Hofsten, 2007; Smith et al., 2014; Street et al., 2011), showing that toddlers preadjusted the orientation of objects before trying to insert them into an aperture, and that around 30 months of age, toddlers began preadjusting already at the beginning of the transport phase, which indicates predictive planning (Jung et al., 2015). The present findings show that just a few months later, between 3 and 3.5 years of age, children are able to mentally rotate more complex asymmetrical shapes, thus suggesting that

predictive planning in the object-fitting tasks may have indeed been based on a mental rotation process.

The present results replicate and extend previous findings of mental rotation in 3.5- to 4-year-olds using a similar task (Pedrett et al., submitted). They also complement several other studies that did not find evidence for mental rotation before 4 to 5 years of age using different tasks (e.g., Estes, 1998; Frick, Ferrara, et al., 2013; Frick, Hansen, et al., 2013; Kosslyn et al., 1990; Krüger & Krist, 2009; Quaiser-Pohl et al., 2010), or only with extensive training (Fernández-Méndez et al., 2018; Krüger & Krist, 2009). Previous mental-rotation tasks typically presented the shapes not only in different orientations, but also in different locations, so that participants needed to imagine a combination of rotation and additional horizontal or vertical motion in order to mentally superimpose the images. In the present task however, the flags could be transferred onto the cutout by mental rotation alone. This suggests that children are able to perform simple mental rotations at 3 to 3.5 years of age, yet their imagery abilities get more sophisticated in the following years, allowing them to increasingly solve mental imagery tasks that require more complex combinations of mental transformations. These results are in line with theories on how children process information from multiple dimensions such as color and shape, suggesting that with increasing age, children can increasingly encode (Siegler, 1976), separate and analyze (Smith & Kemler, 1978), or integrate information from multiple dimensions (Shanteau et al., 2007; Wilkening, 2007).

A further simplification of the present task is that the shape was physically attached to the pivot point, thus implying a clear rotational trajectory. The high affordance character (Jones, 2003) of this task may have prompted the young participants to form a motor plan for how to physically rotate the shape onto the cutout, which may have elicited a mental prediction of how the flag would look during the planned rotation. It is thus possible that the

present task – like object-fitting tasks – tapped into processes of action planning or embodied knowledge that was not (yet) accessible to conscious thought.

In summary, the above-chance success rates of 3-year-olds on the present task bridge the gap between research in toddlers showing preadjustment on object-fitting tasks, and studies with 4- to 6-year-olds using more traditional tasks similar to those used with adults that require a choice between two mirror images. The novel findings suggest that mental rotation may indeed develop continuously, enabling toddlers to predictively rotate an object before inserting it into a hole (Örnkloo & von Hofsten, 2007), and 3-year-olds to succeed in a more traditional forced-choice task when task affordance is high, only one type of motion is involved, and nonverbal response options are clearly visible.

An open question is whether 2-year-olds can mentally rotate asymmetrical shapes and distinguish them from mirror images. To have success in the present task, children needed to perform many cognitive processes correctly. For example, children had to understand the task instructions and to control their eye movements in order to visually compare the two flags and the two cutouts. Then they also needed to correctly interpret the result of this comparison, translate it into a motor response, and inhibit choosing the first flag they saw. Informal observations showed that in some trials, participants easily coped with these task demands, and often looked back and forth between both boards, touched the wrong shape first but then rotated the correct shape, or looked at the wrong flag to double-check while rotating the correct one. Yet, in other trials, participants did not look carefully at the two flags and cutouts and often chose the wrong flag posthaste. A lack of careful encoding of the two choices may therefore be a limiting factor on forced-choice tasks, and is doubtful whether younger children can succeed.

In conclusion, this study provides new information on how mental imagery develops between toddlerhood and preschool age. The present findings suggest that mental rotation

develops continuously, with some mental rotation already before 4 years of age and further development in the following years of life.

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Table 1*All test trials in the order of presentation.*

trial	block	direction	disparity	cutouts	flag pair	correct response
1	1	cw	30°	original	cyan	right
2		cw	30°	mirrored	green	left
3		cw	60°	original	orange	left
4		cw	60°	mirrored	magenta	right
5		cw	90°	original	cyan	left
6		cw	90°	mirrored	green	right
7		cw	120°	original	orange	right
8		cw	120°	mirrored	magenta	left
9	2	ccw	30°	mirrored	magenta	left
10		ccw	30°	original	orange	right
11		ccw	60°	mirrored	green	right
12		ccw	60°	original	cyan	left
13		ccw	90°	mirrored	magenta	right
14		ccw	90°	original	orange	left
15		ccw	120°	mirrored	green	left
16		ccw	120°	original	cyan	right
17	3	cw	150°	original	cyan	right
18		cw	150°	mirrored	green	left
19		cw	180°	original	orange	left
20		cw	180°	mirrored	magenta	right
21		ccw	150°	mirrored	magenta	left
22		ccw	150°	original	orange	right
23		ccw	180°	mirrored	green	right
24		ccw	180°	original	cyan	left

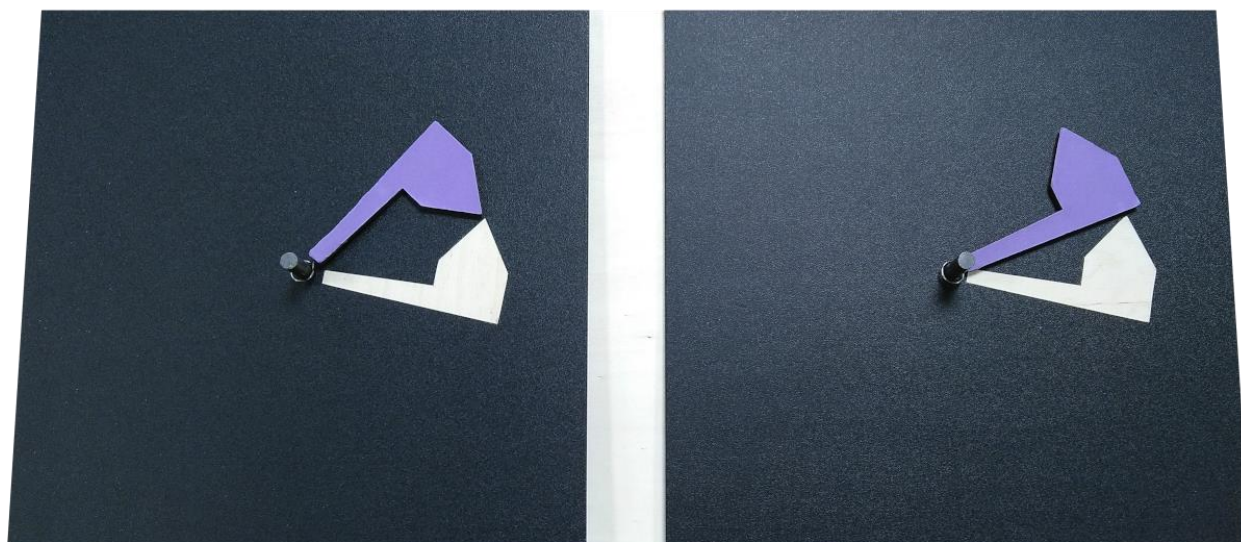


Figure 1

Example of a practice trial.

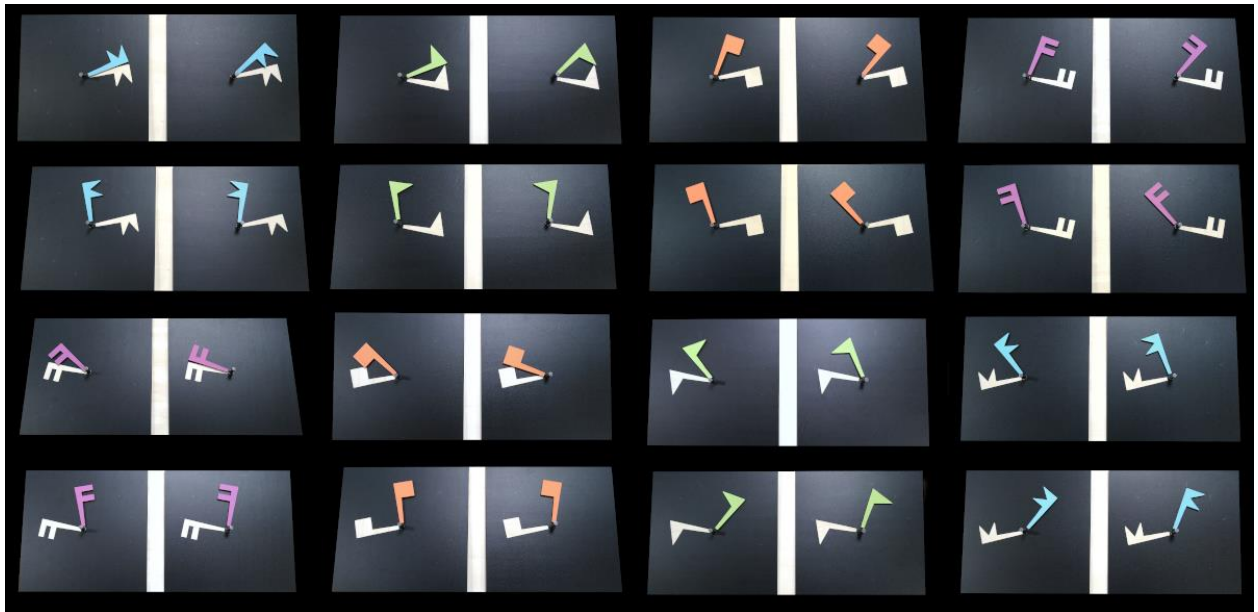


Figure 2

Test trials in Block 1 (rows 1 and 2) and test trials in Block 2 (rows 3 and 4). The trials were presented in the order of reading direction.

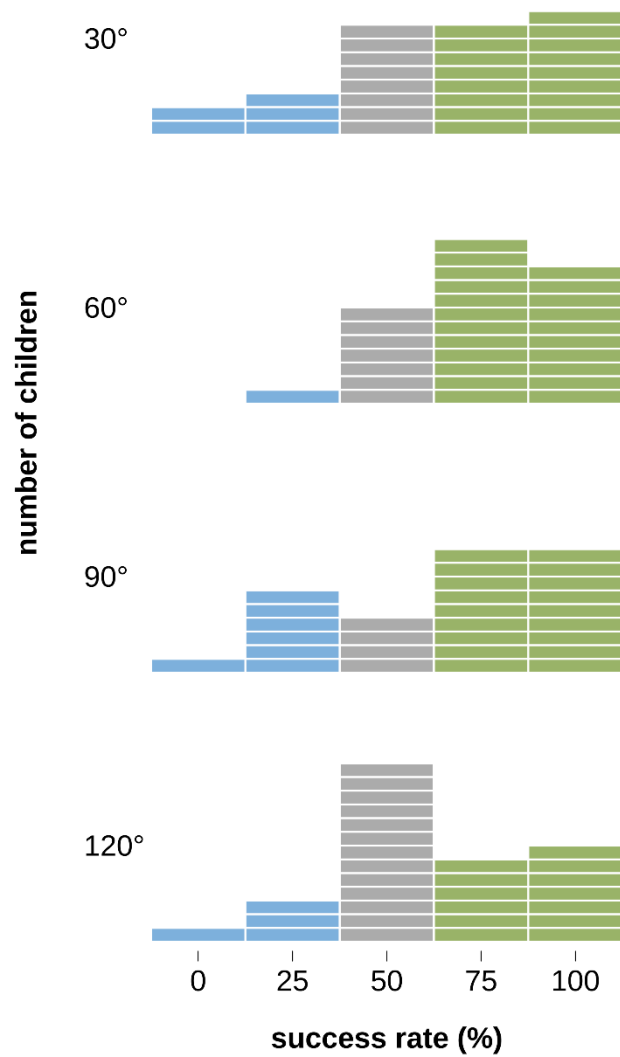


Figure 3

Success rates in Blocks 1 and 2. Each rectangle corresponds to a child. In each disparity, possible success rates were exactly 0, 25, 50, 75, or 100%. It can be seen that more children had success rates above 50% (green) than below 50% (blue).

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