# The positive influence of manual object exploration on predictive grasping for a moving object in 9-month-old infants

**Gloria Gehb** Department of Developmental Psychology, Justus-Liebig-University Giessen, Giessen, Germany

**Claudia Kubicek** Department of Developmental Psychology, Justus-Liebig-University Giessen, Giessen, Germany

**Bianca Jovanovic** Department of Developmental Psychology, Justus-Liebig-University Giessen, Giessen, Germany

**Gudrun Schwarzer** Department of Developmental Psychology, Justus-Liebig-University Giessen, Giessen, Germany

**The present study examined whether infants' manual prediction ability is related to different types of their manual object exploration behavior. Thirty-two 9-month-old infants were tested in a manual prediction task, in which they were encouraged to reach for a temporarily occluded moving object. All infants also participated in a manual exploration task, in which they could freely explore five toy blocks. Infants with a high number of haptic scans in the manual exploration task showed a higher prediction rate in the manual prediction task compared to infants with a low haptic scan score. Reaction times of all infants decreased during the test blocks. However, the reaction time of infants with a high haptic scan score was faster in general. Our findings suggest that object experiences gathered by specific manual exploratory actions, such as haptic scans, are related to infants' predictive abilities when reaching and grasping for a temporarily occluded moving object.**

## Introduction

One of the most important things in our daily life is the interaction with objects. In order to act in a successful and effective way it is necessary that certain assumptions about possible events are made, even though we are often not explicitly aware of these assumptions. In particular, when we want to grasp for a moving object we have to predict where its future position will be. This also applies when the moving object is temporarily occluded because then we have to anticipate the object's motion path that is not visible. For this we need a mental representation of the object and its motion to make a prediction about the object's location as well as the time of its reappearance (Jonsson & von Hofsten, 2003). Some predictive abilities while grasping an object exist even early in infancy, especially when an object moves linearly and when the whole movement is visible (Rosander & von Hofsten, 2004; von Hofsten & Rosander, 1997). However, little is known about which developmental factors are related to infants' predictive grasping. Prior studies have shown that there is a relation between infants' self-produced manual object exploration and their visual–spatial object processing (e.g., Kubicek, Jovanovic, & Schwarzer, 2017; Soska, Adolph, & Johnson, 2010; for an overview, see Kubicek & Schwarzer, 2018; Schwarzer, 2014). If we assume that predictive grasping also relies on visual–spatial processes, we should find a relation between predictive grasping and manual object exploration as well. Accordingly, in the present study, we examined this relation in a sample of 9-month-old infants.

### Spatial prediction

Interaction with a moving object requires more than just visual tracking of the object. There must also be a mental representation of its movement if it is temporarily occluded. In order to predict the object's future location, the object's velocity and direction of movement must also be predicted. Such spatial predictions ensure that the gaze reaches the future location of the

Citation: Gehb, G., Kubicek, C., Jovanovic, B., & Schwarzer, G. (2019). The positive influence of manual object exploration on predictive grasping for a moving object in 9-month-old infants. *Journal of Vision*, *19*(14):13, 1–15, https://doi.org/10.1167/19.14.13.

https://doi.org/10.1167/19.14.13 Received November 15, 2018; published December 12, 2019 ISSN 1534-7362 Copyright 2019 The Authors

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License.

Downloaded from jov.arvojournals.org on 04/11/2021

moving object before the object itself has reached it. In the case of object occlusion, spatial predictions make it possible to look at the location of the object's reappearance before the object is visible again (Rosander & von Hofsten, 2004). It has been shown that even 2-month-old infants were able to anticipate the future location of a moving object with their gaze if it moved visibly in front of them. This ability improved strongly in the following months (von Hofsten & Rosander, 1997; von Hofsten, Vishton, Spelke, Feng, & Rosander, 1998). Infants were also able to anticipate visually the location of reappearance of a moving temporarily occluded object. The performance in these tasks increased with age and was influenced by certain factors of the task, such as the motion path of the object and the duration of occlusion (Gredebäck & von Hofsten, 2004; Rosander & von Hofsten, 2004; van der Meer, van der Weel, & Lee, 1994; von Hofsten, Feng, & Spelke, 2000; von Hofsten, Kochukhova, & Rosander, 2007; Woods, Wilcox, Armstrong, & Alexander, 2010). At 9 months, infants were able to look in advance at the correct position of recurrence of an object moving linearly when it was occluded for a few seconds (Gredebäck, von Hofsten, & Boudreau, 2002; Gredebäck, von Hofsten, Karlsson, & Aus, 2005).

In comparison to merely looking at the object, it is even more difficult for an infant to predict the movement of an object in order to grasp it successfully. In this case more visual–spatial processing steps and higher demands regarding action planning and working memory are needed compared to a purely visual prediction. An infant has to consider the time and direction of the movement of their own hand toward the object as well as the time and direction of the object movement itself to be able to grasp it as soon as the object is within reach. If the object's trajectory is occluded momentarily, an infant also has to integrate the duration of the invisible object movement as well as anticipate its location and time of reappearance in order to grasp it (Jonsson & von Hofsten, 2003).

Von Hofsten (1980) was one of the first researchers who investigated infants' predictive grasping of a moving object. Infants tried to grasp an object that was rapidly moving in their direction. Even 18-week-old infants reached and grasped predictively, as they initiated their arm and hand movements before the object was within reach. Regarding infants' predictive grasping of a moving temporarily occluded object, van der Meer et al. (1994) investigated two infants aged from 4 to 12 months and presented a horizontally moving, temporarily occluded object to the infants. At 5 months, the infants were already able to visually anticipate the location of the objects' reappearance. Infants' grasping, however, was reactive. They did not initiate their grasping before the object was visible again. Not until 8 months were they able to predictively grasp the temporarily occluded moving object. In three different conditions, Spelke and von Hofsten (2001) compared 6-month-olds regarding their predictive reaching behavior. In one condition, the moving object was visible for the whole time; in the two other conditions, the object disappeared behind a small or a large occluder. Predictive grasping could be observed in the completely visible condition but it almost disappeared in both occlusion conditions. Very similar results were found in the study by Hespos, Gredebäck, von Hofsten, and Spelke (2009), also indicating less predictive grasping in 6- and 9-month-olds in the occlusion condition. Jonsson and von Hofsten (2003) used several types of occlusion in their study with 6-month-old infants. They also had an occlusion and a visible condition as well as an additional condition in which they dimmed the light down to occlude the object. In all conditions there were three different occlusion durations. The results showed that there was no improvement of predictive grasping across the trials in the occlusion condition. Infants in the dimming condition, however, increased their predictive grasping across the different trials. The authors explained these results by means of the competition hypothesis, which implies that the second object (occluder) distracted the babies' attention and therefore weakened their mental representation of the moving target object. This was not the case in the dimming condition in which no second object was used. One of the most recent studies on predictive grasping in infants manipulated the size of the occluder, as well as the velocity of the target object in order to find out if the duration of occlusion is the crucial factor for the performance in such tasks (van Wermeskerken, van der Kamp, te Velde, Valero-Garcia, Hoozemans, & Savelsbergh, 2011). They tested 7-, 9- and 11-month-old infants. The results showed that older infants grasped the object more often in a predictive manner. Independent of age, predictive grasping actions decreased with increasing duration of occlusion. These results indicated that the older the infants were, the less they were affected by occlusion.

To sum up, the results of previous studies showed that infants from 4-months-old onwards were able to grasp a fully visible, linearly moving object predictively. It was not until 8 months that infants were able to grasp a moving temporarily occluded object predictively (van der Meer et al., 1994). Here, the duration of occlusion was crucial for infants' predictive grasping performance (van Wermeskerken et al., 2011). The smaller the occluder, (i.e., the lower the occlusion duration), the better was the infants' performance.

Downloaded from jov.arvojournals.org on 04/11/2021

## Fine motor skills and visual–spatial object processing

A number of studies have shown a relation between infants' fine motor skills and their visual–spatial object processing (for an overview, see Kubicek & Schwarzer, 2018; Schwarzer, 2014). For example, Slone, Moore, and Johnson (2018) investigated the relation between manual object exploration and mental rotation ability in 4-month-old infants. The infants had the opportunity to explore objects by wearing sticky mittens. The mittens helped the infants, who were not yet able to grasp on their own, to manipulate the toys. Subsequently, the infants were given a mental rotation test with a similar object as the one they had explored. A higher novelty preference (i.e., a better mental rotation ability) was only shown by the 4-month-olds, who prior to the mental rotation task had extensively explored the objects with the sticky mittens, as compared to same-aged infants who had explored the objects less extensively or only after the mental rotation task (Slone et al., 2018). Slone et al. (2018) concluded that infants' visual–manual object exploration improved their understanding of the different perspectives of the object, which they then used in the following mental rotation task. Möhring and Frick (2013) found similar results in 6-month-old infants by using a violation-of-expectation paradigm to test their mental rotation ability. In one condition, infants were encouraged to manually explore the test objects; in the other condition, infants only visually observed the experimenter manually exploring the test objects. The results indicated that 6-month-olds only showed mental rotation performance if they had had the opportunity to explore the test objects manually before. If the infants had just observed the experimenter exploring the object, they were not able to master the mental rotation task. Only at 10 months of age were infants able to master the same mental rotation task without having the prior opportunity to explore the objects manually.

Other studies tested the relation between specific manual object exploration procedures used by infants and their visual–spatial object processing. For example, Soska et al. (2010) encouraged 4.5- to 7.5-month-old infants to freely explore four different toy blocks for 60 s. The authors analyzed three specific types of infants' manual exploration actions: fingerings, transfers, and rotations, and counted how often the infants performed these actions on the objects. A fingering was counted if infants moved their fingers over the surfaces and edges of an object. An action was rated as a transfer if the infants passed an object from one hand to the other. If infants turned an object at least 90° in one direction the action was counted as a rotation. Soska et al. (2010) used an object-completion task to evaluate infants' visual–spatial object processing. Here, infants were habituated to a wedge-shaped object in a limited view. During test trials the infants viewed the corresponding complete 3D object or an incomplete object, which was made up of only two sides. Results demonstrated that infants' manual exploration performance had a positive influence on their ability to complete the invisible parts of the target 3D objects. Infants with a high overall score across fingerings, transfers, and rotations looked at the incomplete object (novelty preference) more often than at the complete object. It seems that they understood what the 3D object really looked like. Gerhard, Culham, and Schwarzer (2018) investigated the relation between the same manual exploration actions as Soska et al. (2010) and infants' preference for 3D objects. In a preferential looking task, 7-month-old infants saw a real object or its pictorial counterpart. The results showed that infants with a high score in fingerings preferred the real object compared to its pictorial counterpart, whereas infants with a low fingering score showed no preference. The authors concluded that the experience with such a specific manual exploratory action like fingerings might have facilitated the understanding of objects' spatial (2D and 3D) format. In addition, Schwarzer, Freitag, and Schum (2013) revealed a significant relationship between the three manual exploration actions and the mental rotation ability in 9-month-olds. Infants in Schwarzer et al.'s (2013) study were habituated to a simplified Shepard-Metzler object (Shepard & Metzler, 1971). At test, either the familiar further rotated object or its mirror object was presented. The infants with a high exploration score looked at the mirror object more often than the infants with a low exploration score. This indicates that only the infants with a high exploration score were able to mentally rotate the object.

Until now, only one study has tried to reveal the relation between infants' fine-motor skills and their ability to predict the movement of an object (Kubicek et al., 2017). In this study, 7-month-old infants participated in a manual object exploration procedure according to Soska et al. (2010) and in a prediction task. In this prediction task, two target objects were attached to the right and left side of a box that was covered by a rectangular board (occluder). During the familiarization phase, the entire object array moved around its vertical axis, thereby uncovering the target objects, which alternately appeared on the right or left side of the object array. In the test phase, the object array rotated around its horizontal axis and the target objects appeared at the top or the bottom. It was measured how often the infants were able to anticipate with their gaze when and where the target objects would appear. In this study, 7-month-old infants with a high manual exploration score showed a significantly higher visual prediction rate than infants with a low

Downloaded from jov.arvojournals.org on 04/11/2021

manual object exploration score. This means that infants with a high manual object exploration score looked at the location of the object's expected appearance before its physical appearance more often than infants with a low score. The authors concluded that advanced manual exploration skills seem to facilitate infants' visual prediction of the location where the moving, temporarily occluded object would reappear.

### Present study

Previous studies showed a facilitating relation between visual–manual experiences and visual–spatial abilities in infants (e.g., Gerhard et al., 2018; Schwarzer et al., 2013; Soska et al., 2010). However, until now only Kubicek et al.'s (2017) study investigated the relation between infants' manual object exploration skills and their predictive abilities. The authors found that manual object exploration facilitated the visual ability to predict the location of reappearance of a moving temporarily occluded object. To extend these findings, the goal of the present study was to investigate whether there is also a relation between infants' manual object exploration behavior and their manual visual–spatial prediction abilities. As pointed out above, predictive grasping emerges later than predictive looking. The reason for this decalage has not been uncovered yet; however, it might be possible that manual prediction is driven by different processes than visual prediction and this might have implications for the link with manual exploration. However, if predictive looking and predictive grasping rely on similar processes and only differ in the complexity of processes involved in planning eye movements as compared to planning grasps, we should find a similar link with infants' manual exploration scores as reported by Kubicek et al. (2017). Specifically, we sought to investigate, whether specific exploration procedures are related to infants' manual predictive abilities. Soska et al.'s (2010) study already hints at three potentially relevant types of exploratory actions that are crucial for gaining information about objects, namely haptic scans (fingerings), transfers, and rotations. Based on these findings, we investigated which of these three actions is related to predictive grasping of 9-month-old infants. Furthermore, we examined if there are learning effects, and thus, if infants synchronize their own grasping movement to object's movement over time. As previous studies have shown that predictive grasping for a temporarily occluded object only emerges around 8 months of age (van der Meer et al., 1994), we investigated this question in 9-month-old infants.

## Method

### Ethics statements

The current study was conducted in accordance with the German Psychological Society (DGPs) research ethics guidelines. The Office of Research Ethics at the University of Giessen approved the experimental procedure and the informed consent protocol. Written informed consent was obtained from infants' parents prior to their participation in the study.

### Participants

Sixty-five 9-month-old infants participated in the study. Thirty-three of these were invited, but were excluded from the data analysis, because of fussiness during the grasping task ($n = 3$), crying during the grasping task ($n = 19$), or failure to fulfill the inclusion criteria (see section, Data analysis) for both tasks ($n = 1$) or only for the grasping task ($n = 10$). The final sample thus included 32 healthy, full-term infants (18 male and 14 female). Their mean age was 9.64 months ($M = 293.09$ days; $SD = 11.70$; range = 275–316 days). All infants were from middle-class families.

### General procedure

All infants participated in a manual prediction task, as well as a manual object exploration task. The order of the tasks was randomized between infants. Each infant was tested individually. After testing, the babies received a small toy and a certificate as a reward.

### Manual prediction task

#### *Stimuli*

The stimuli of the manual prediction task consisted of two target objects that were attached to a base object. The target objects consisted of two differently sized and differently colored spheres (1.5 cm and 5 cm in diameter). The spheres were made of wood and were painted red with yellow dots or yellow with red dots (see Figure 1). In contrast to Kubicek et al. (2017), we attached spheres to the apparatus instead of toys, in order to make the whole setup appear as a single object with different parts instead of an arrangement of different objects. Another reason why we used spheres instead of toys was that the spheres are more suitable to 9-month-old infants' hand size. Furthermore, the target objects varied in size and color to make them more

Downloaded from jov.arvojournals.org on 04/11/2021

Figure 1. Target objects for the manual prediction task.

interesting for the infants and to maintain their attention.

The base object (see Figure 2) consisted of a rectangular block and an occluder. The body of the rectangular block was 20 cm wide, 35 cm high, and 10 cm deep and consisted of black lacquered wood. The block was covered by a larger, thin board (22.5 cm wide × 47.5 cm high) attached to the block, which was covered with black cloth so that the whole base object was black. This board served as an occluder, so that the block was completely invisible when viewed from the front. On the top and at the bottom of the block, the two target objects were attached with a magnet. One of the target objects (large or small sphere) was mounted on the top and the other one on the bottom. The yellow spheres were always attached at the bottom to compensate the low lighting conditions on the bottom. Thus, there were two different conditions for the placement of the target object (a) large red sphere on top and small yellow sphere at the bottom, or (b) small red sphere on top and large yellow sphere at the bottom. The object placement was counterbalanced between participants.

### *Apparatus*

The entire stimulus array described above was presented dynamically. A programmable electric motor was used to move the base object with the attached target objects (object array). The movement always started from the frontal position of the object array, in which the occluder covered the block with both targets. The object array could rotate around its horizontal axis

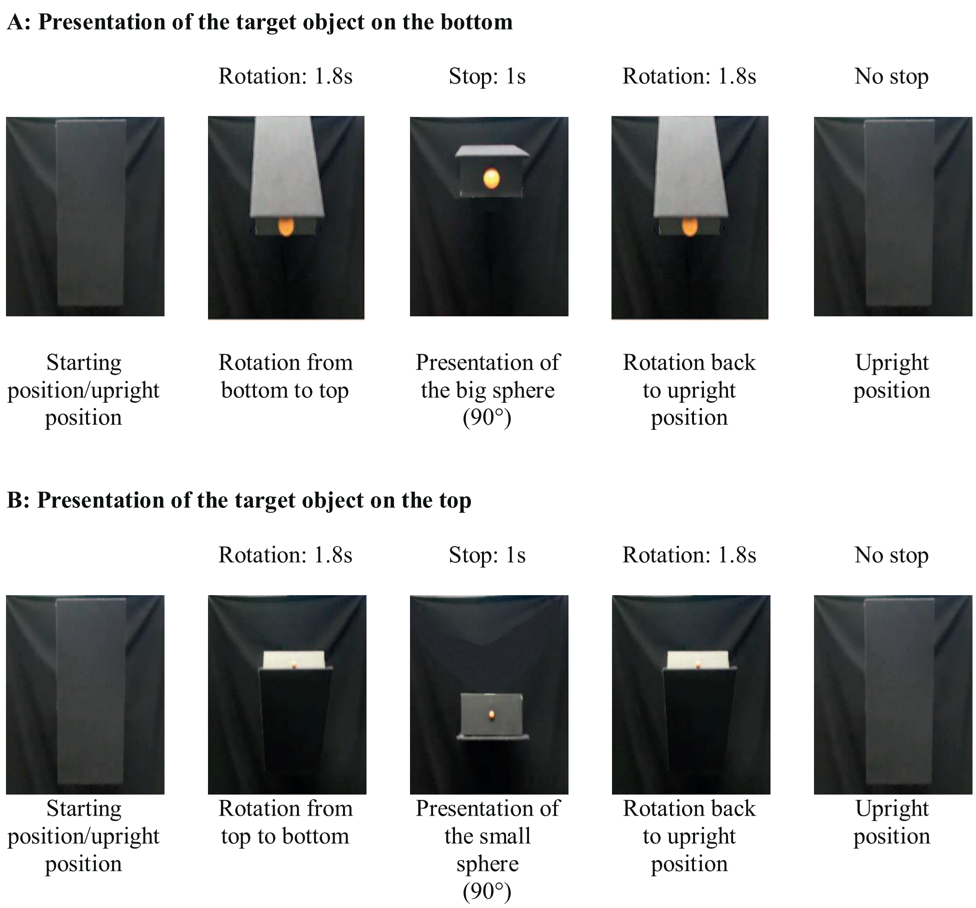


Figure 2. Presentation of the target objects attached to the base object during the familiarization phase. One trial with the presentation of the target object at the bottom (A) and one with the target object at the top (B).

Downloaded from jov.arvojournals.org on 04/11/2021

with a rotation velocity of 50°/s, covering an angle of 90°. During this movement, one of the target objects that was attached at one of the sides of the block (i.e., top or bottom, respectively) was gradually uncovered and became visible (see Figure 2). When the object started to move, the upper and lower spheres became partly visible after 900 ms. As soon as the array reached the final position, with the target object facing the infant, it stopped moving. This stationary phase lasted for 1 s in the familiarization phase or at least 5 s in the test phase. Afterward, the object array rotated back to its starting position, thereby gradually covering the target object again. This movement was then repeated with the other side of the object array (top vs. bottom). The time period between the full occlusion of the target objects (starting position) and the moment when the target object became visible slightly differed between the small and the big sphere. In the small sphere condition the object rotated for 1.9 s until it was fully visible, and in the big sphere condition it rotated for 1.5 s. Whether the objects' movement started from top to bottom or vice versa was counterbalanced across the sample. The setup was placed in a quiet room. Behind the object array and laterally at an angle of 45° was a black screen to avoid any distraction. To the left of the black screen a camera (Sony HDR-SR12; Sony Corp., Tokyo, Japan) was placed that recorded the whole task. The camera was positioned so that the infant and the object array were completely visible.

### Procedure

Before the task began, parents were asked to indicate which hand the infant typically uses when he or she reaches for an object. If the parents were unsure, we presented an object unrelated to the task three times in the middle of the table and counted with which hand the baby reached for the object most frequently. This hand was then determined as the dominant hand. Additionally, infants had the opportunity to explore each target object (large and small sphere) visually and manually for 20 s. During this exploration phase, the babies sat at a table on the lap of their caregivers, where the objects were presented in reaching distance.

After this warm-up phase, the manual prediction task started. The caregivers sat in a chair with their infants on their laps. The height of the chair was adjusted so that the infants looked at the middle of the base object. This corresponded to a distance of 100 cm from the child's eyes to the floor and a distance of 60 cm (in the familiarization phase) and 30 cm (in the test phase) from the object array. To prevent parents from influencing the behavior of their infants, they were asked not to interact with their infants during the experiment.

The prediction task consisted of a familiarization phase, a demonstration phase, and a test phase. During the familiarization phase, infants only looked at the moving object array. The familiarization phase consisted of eight trials, divided into two blocks. In one block, the object array moved from the top to the middle position, thereby presenting the target object that was attached on the top. In the second block, the object array moved from the bottom to the middle position, presenting the target object that was attached on the bottom. The target objects of each block were presented four times (see Figure 2). Thus, during the familiarization phase, the infants became visually familiar with the movement of the object array and with the two target objects.

After the familiarization phase, the demonstration phase started. The object array rotated once more in each direction and stopped when it reached the middle position and the target object was fully visible. The experimenter took the respective sphere, gave it to the infant, and put it back on the base object afterward. During this phase, infants became familiar with the opportunity to grasp the target objects.

The subsequent test phase encompassed 16 trials, divided into four blocks of four trials for each movement direction (upward or downward), presented in an alternating order. The test phase started with the starting position (the full occlusion of the target objects), which lasted about 2 s. Then the object array moved to the front and reached the middle position with the target objects in full view; there the target objects were presented for at least 5 s. Afterward, the object array rotated back to the starting position. During the test phase, infants had the opportunity to grasp the target objects with their hand while the object array was moving. If the infants did not attempt to grasp for the object, the object rotated back in its starting position after 7 s. In order to adapt the procedure to the looking and grasping behavior of the infant, the movement of the object array was controlled manually by the experimenter. By pressing a button the experimenter controlled when the object array rotated to the front (target presentation) or back to the starting position (full occlusion). We did so to ensure that the infants looked toward the object array when the movement of the object array started, and to prevent the infants from touching the object during the rotation. Caregivers were asked to hold back the infant's nondominant hand (mostly left). They were also told to hold back the dominant hand when the object rotated back to its starting position, but to release it as soon as they were told by the experimenter. Furthermore, if the infants grasped the target object, the parents were asked to put it back on the base object as soon as possible.

Downloaded from jov.arvojournals.org on 04/11/2021

## Manual object exploration task

### Stimuli

Following the study by Schwarzer et al. (2013), we used five colorful toy blocks with different shapes and textures as stimuli. The objects were made of wood, plastic, or fabric, and were decorated with colorful pictures to make them attractive for the infants. The side lengths of the objects ranged from 2 cm to 10 cm, so that the infants could grasp them well (see Figure 3). In order to determine infants' general manual exploration behavior, we used age-appropriate toys of various shapes and colors and not the target stimuli of the manual prediction task.

### Procedure

Infants were seated on their parents' laps, so that they were in a comfortable position to explore the objects. The whole procedure was recorded by a video camera (JVC GG-PX100; JVC Ltd., Yokohama, Japan), which was placed on the wall opposite the infant. Parents were instructed not to interact with their babies, so as not to influence their behavior. The experimenter offered the infant one of five toys at a time, in a counterbalanced order across the sample. The experimenter put the toy in the middle of the table, so that the infant could reach and explore it. If the infant did not grasp the object and start exploring it within 10 s after presentation, the experimenter handed the toy to her or him. Timing began as soon as the infant touched the object and ended after 40 s of cumulative spontaneous exploration. If the object was dropped or the infant stopped exploring, the timing was stopped until the infant touched the object again. If the infant did not start exploring the object again within 5 s after presentation, the experimenter handed the object to the infant. Each object presentation was stopped as soon as the infant had explored the toy for 40 s. At this point, the experimenter took the object from the infant's hand or from the table. Afterward, the presentation of the next object started.

## Data analysis

The video recordings of the two tasks were evaluated according to specific criteria, which are described in the following sections.

Figure 3. Stimuli of the manual exploration task.

### Manual prediction task

The video recordings from the test phase of the manual prediction task were evaluated frame by frame with the program, VirtualDubMod 1.5.10.3. Only infants who saw all four test blocks and made at least four attempts to grasp the target objects were evaluated. Out of a total of 518 trials, 23 trials were excluded because the infants did not see the beginning of the objects' movement ($n = 9$), caregivers released the arm too late ($n = 7$), or the experimenter committed an error ($n = 7$), so that 495 valid trials remained. Within the 495 valid trials, the infants reached for the target objects on 347 trials (70%). For analysis, we focused on infants' grasping attempts toward the object array. An arm movement toward the object array was defined as a grasping attempt if the hand came in immediate reach of the object without necessarily touching it. Thus, the infants' arm had to be stretched at least half so that the hand was in immediate vicinity of the object array to be counted as valid grasping attempt. We chose this criterion to differentiate grasping attempts and coincidental arm movements. The average time until the upper and lower spheres became visible after the array had started to move was 900 ms. Various studies showed that 300 ms are needed to initiate a planned action (e.g., Hespos et al., 2009; Jonsson & von Hofsten, 2003; von Hofsten et al., 1998). Infants' grasping behavior was classified into predictive and reactive grasping. A grasping action was considered predictive if the infants started the grasping movement before they could see the target object (sphere), in order to exclude the possibility that grasping was merely triggered by the sight of the objects. As it took about 900 ms from the start of the movement of the object array until the respective sphere became visible, and as initiating a grasping movement is assumed to require 300 ms (e.g., Hespos et al., 2009; Jonsson & von Hofsten, 2003; von Hofsten et al., 1998), we classified any grasping attempt that was started within 1,200 ms as predictive. Grasping attempts that were only started after 1,200 ms were considered reactive, because we assumed that the grasping action was only planned after the target object was partly visible again.

The prediction rate was calculated as the number of predictive grasping attempts divided by the total number of all grasping attempts (number of predictive grasping actions / predictive + reactive grasping actions). Fifty percent of all videos were rated by a second person, to calculate the interrater reliability for the number of all performed grasping actions (predictive and reactive together) and the number of predictive grasping actions. For the number of all performed grasping actions as well as the number of predictive grasping actions, the interrater reliability exceeded 0.9 (Pearson's $r$).

Downloaded from jov.arvojournals.org on 04/11/2021

### *Manual exploration task*

Based on the findings from previous studies (e.g., Schwarzer et al., 2013; Soska et al., 2010), we focused on three specific manual exploration actions (haptic scans, transfers, and rotations; we renamed fingerings to haptic scans). Only explorative actions during which the object was simultaneously visually inspected for at least 0.5 s were considered. An action was considered as haptic scan, if the infants scanned the surface or the contours of an object with their fingers. If the infants passed the object from one hand to the other, this was considered as a transfer. It was only counted as a transfer if the object was held in both hands for less than 5 s. A rotation was counted if the object was turned at least 90° in one direction (clockwise, counterclockwise, or depth). We counted the individual exploration actions (haptic scans, transfers, rotations) for each object and then calculated the sum across all objects. A second rater also evaluated the infants' manual exploration behavior in 50% of the video recordings. The interrater reliability exceeded 0.9 (Pearson's $r$) for haptic scans, transfers, and rotations. Based on the frequency of haptic scans, transfers, and rotations, we assigned the infants to two exploration groups. This was done using the median split. Infants above the median were classified as high-explorers and infants below the median as low-explorers. This was calculated for every manual exploration action separately. Accordingly, each infant produced three scores, a haptic scan score, a transfer score, and a rotation score. As an example, the same infant could be a high scorer in rotation but a low scorer in transfer. For the descriptive values please see Table 1.

## Results

To analyze the data we used the program SPSS, version 26. For all statistical analyses we applied a significance level of $\alpha = 0.05$. Preliminary analyses on infants' prediction rates revealed no significant effects of infants' exact age, task order (manual prediction task or manual exploration task first), first direction of object movement (top to bottom or vice versa), or side of target position (small or big sphere on top). For these variables all $p$-values were equal or greater than 0.085. For infants' manual exploration score, the preliminary analyses showed no effects of infants' age and the task order (manual prediction task or manual exploration task first). Also, here all $p$-values were greater than 0.077). Thus, these factors were collapsed across these variables for subsequent analyses.

Furthermore, we checked if the number of male and female infants was equal in each of the different manual exploration groups (high vs. low) with a $\chi^2$ test. For the transfer as well as rotation groups, the distribution of male and female infants was equal in the corresponding high- and low-exploring groups ($p$s $\geq 0.688$). However, for the haptic scan group, there was a significant, unequal distribution of female and male infants in the high (5 male, 9 female) and low (13 male, 5 female) exploration group, $p = 0.039$. Thus, for further calculations with the variable haptic scan group, we considered the factor gender as a between-subjects variable.

In order to investigate our main question (Which of the three exploration actions [haptic scans, transfers, rotations] were related to infants' predictive grasping behavior?) for each of the three exploration groups (high vs. low), we calculated a separate univariate ANOVA (Bonferroni-corrected) on infants' prediction rates, respectively. Because of the unequal distribution of male and female infants in the high and low haptic scan groups we added gender as a between-subjects variable. Before we performed these univariate ANOVAs, we used the Shapiro-Wilk test to check if the prediction rate was normally distributed over the groups (high vs. low) of the different exploration actions (haptic scans, transfers, rotations). The normal distribution was violated only in the low haptic scan group, $p = 0.026$ (see below how this result was taken into account). For the depiction of the individual data points see Figure 4. The prediction rate was approximately normally distributed for both (high vs. low) transfer groups ($p \geq 0.148$) as well as for both (high vs. low) rotation groups ($p \geq 0.123$).

| | Haptic scans | Transfers | Rotations |
|---|---|---|---|
| Mean | 11.19 | 2.91 | 10.00 |
| Standard deviation | 7.67 | 3.13 | 5.28 |
| Range | 0–31 | 0–13 | 2–21 |
| Median | 9 | 2 | 8 |
| $n$ per exploration group | 14 high exploration (≥10 haptic scans) | 14 high exploration (≥3 transfers) | 15 high exploration (≥9 rotations) |
| | 18 low exploration (≤ 9 haptic scans) | 18 low exploration (≤2 transfers) | 17 low exploration (≤8 rotations) |

Table 1. Descriptive values for haptic scans, transfers and rotations.

Downloaded from jov.arvojournals.org on 04/11/2021

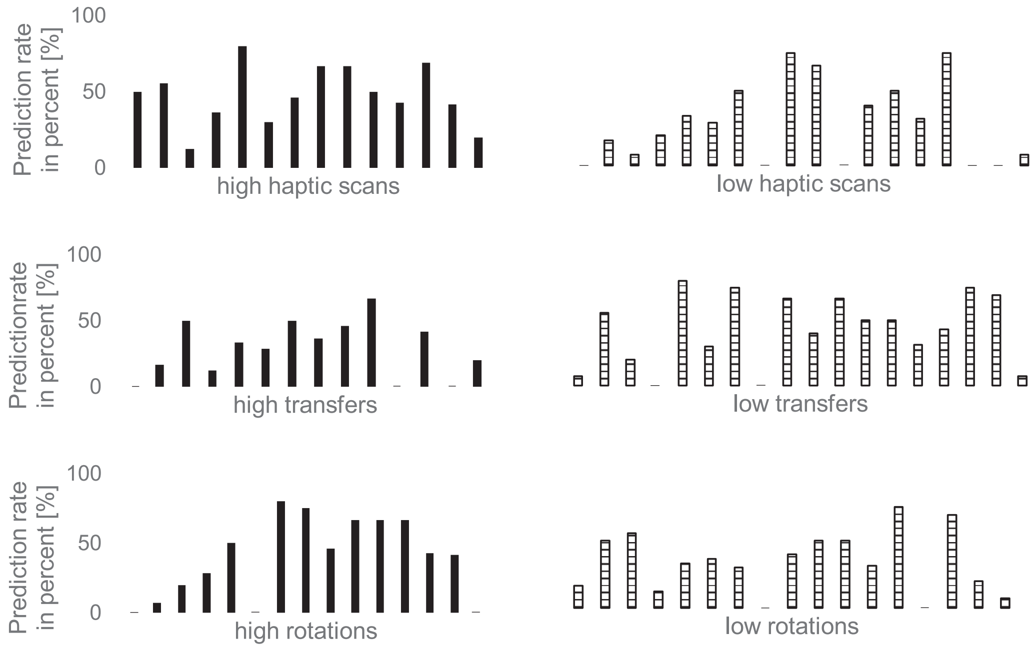


Figure 4. Averaged prediction rate for each infant (prediction rate averaged across the four test blocks) separate for the various exploration actions (haptic scans, transfers, rotations) in the different groups (high vs. low). In the different rows you find the prediction rates for the groups (high vs. low) of the three different exploration actions (Row 1: haptic scans, Row 2: transfers, Row 3: rotations). For each graph the black columns represent the prediction rate for the high-exploring infants and the striped columns the prediction rate for the low-exploring infants.

With regard to the haptic scan group, the ANOVA revealed a significant main effect, $F(1, 28) = 7.952$, $p = 0.009$, partial $\eta^2 = 0.221$ (Bonferroni-corrected). Infants in the high haptic scan group had a significantly higher prediction rate, $M = 47.69\%$, $SD = 19.23\%$; $SEM = 5.14\%$, compared to the infants in the low haptic scan group, $M = 27.82\%$, $SD = 26.62\%$; $SEM = 6.27\%$. For the factor gender, the ANOVA did not reveal a significant main effect, $F(1, 28) = 1.745$, $p = 0.197$, partial $\eta^2 = 0.059$, as well as no significant interaction between haptic scan group and gender, $F(1, 28) = 1.530$, $p = 0.226$, partial $\eta^2 = 0.052$. Due to the violation of the normal distribution in the low haptic scan group, we performed bootstrapping for the corresponding univariate ANOVA. We calculated a 95% percentile confidence interval with 1,000 bootstrap samples. Based on a bootstrapping sample of 995 generated values, again, the difference between the high and low haptic scan group was significant $p = 0.001$, 95% CI [−54.212, −15.926]. Based on the evidence from existing simulation studies, we assume the relative robustness of ANOVAs to violations of the assumptions (Berkovits, Hancock, & Nevitt, 2000; Wilcox, 2012).

Regarding the transfer group, the univariate ANOVA did not show any significant main effect, $F(1, 30) = 2.465$, $p = 0.127$, partial $\eta^2 = 0.076$. Infants of the high transfer group ($M = 28.71\%$, $SD = 21.22\%$; $SEM = 5.67\%$) did not differ from infants in the low transfer group ($M = 42.58\%$, $SD = 27.22\%$; $SEM = 6.41\%$).

The univariate ANOVA regarding the rotation group also did not reveal any significant main effect, $F(1, 30) = 0.364$, $p = 0.551$, partial $\eta^2 = 0.012$. High rotation infants ($M = 39.43\%$, $SD = 28.68\%$; $SEM = 7.40\%$) and low rotation infants ($M = 33.94\%$, $SD = 22.66\%$; $SEM = 5.49\%$) had an equal prediction rate. The prediction rates of the different exploration groups are shown in Figure 5.

In order to investigate if there were learning effects on infants' manual predictions across the four blocks, we conducted a further analysis. We examined whether infants' anticipations become better synchronized with

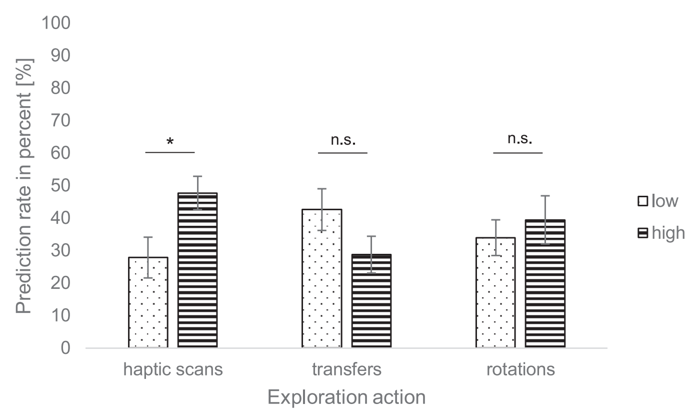


Figure 5. Prediction rate in percent (%) separated for the three different exploration groups (haptic scans, transfers, rotations). Error bars indicate the standard error of the mean. *$p < 0.05$.

Downloaded from jov.arvojournals.org on 04/11/2021

target appearance over the four test blocks, regardless of whether they were classified as predictive or reactive. To this end, we analyzed infants' reaction times. Since not every infant grasped in each block, we included only those infants who grasped at least once in each block ($N = 20$, haptic scans: high = 9, low = 11; transfers: high = 8, low = 12, rotations: high = 9, low = 11). We conducted three separate repeated-measures ANOVAS (Bonferroni corrected) on infants' reaction times, in which the four test blocks served as within-subject variable and haptic scan group (low vs. high), transfer group (low vs. high), and rotations (low vs. high) served as the respective between-subjects variables. Before we computed the analyses, we used the Shapiro-Wilk test to check if the data for the different exploration actions are normally distributed. There were violations of the normal distribution in the first test block only in the low exploration groups of all three exploration actions (low haptic scans: $p = 0.017$, low transfers: $p = 0.012$, and low rotations: $p = 0.004$).

Regarding haptic scans, the repeated measures ANOVA showed a significant main effect of the haptic scan group, $F(1, 18) = 9.700$, $p = 0.017$, partial $\eta^2 = 0.279$, as well as a significant main effect of blocks, $F(1.819, 32.742) = 9.700$, $p = 0.001$, partial $\eta^2 = 0.350$ (Block 1: $M = 3{,}058.50$ ms, $SEM = 308.29$; Block 2: $M = 1{,}677.67$ ms, $SEM = 346.11$; Block 3: $M = 1{,}501.50$ ms, $SEM = 336.19$; and Block 4: $M = 1{,}300.33$ ms, $SEM = 346.59$). There was no significant interaction between haptic scan group and blocks, $F(1.819, 32.742) = 1.446$, $p = 0.250$, partial $\eta^2 = 0.074$. Hence, infants of the high haptic scan group had a faster reaction time compared to infants in the low haptic scan group, but it was not related to the test blocks.

With regard to the transfer group, there was no significant main effect indicated by the repeated-measures ANOVA, $F(1, 18) = 0.658$, $p = 0.428$, partial $\eta^2 = 0.035$. However, there was a significant main effect of blocks, $F(1.693, 30.480) = 8.195$, $p = 0.002$, partial $\eta^2 = 0.313$. The reaction times of the different blocks were the same as the corresponding values of the repeated-measures ANOVA with regard to the haptic scan group, because the main effect blocks relies on the reaction times of the different blocks averaged across the high/low exploration groups. The interaction between transfer group and blocks was not significant, $F(1.693, 30.480) = 0.304$, $p = 0.704$, partial $\eta^2 = 0.017$.

With regard to the rotation group, there was also no significant main effect, $F(1, 18) = 0.377$, $p = 0.547$, partial $\eta^2 = 0.020$, but again a significant main effect of blocks, $F(1.732, 31.173) = 10.469$, $p = 0.001$, partial $\eta^2 = 0.368$. The ANOVA did not reveal a significant interaction between rotation group and blocks, $F(1.732, 31.173) = 1.038$, $p = 0.081$, partial $\eta^2 = 0.136$.

Since all three analyses showed a significant main effect for blocks, we calculated a post hoc $t$ test for paired samples. Due to the violation of normal distribution in the first test block, we used bootstrapping with a generated sample size of 1,000 for this calculation. A pairwise comparison between Block 1 and Block 4 showed a significant difference between these blocks, $t(19) = 3.571$, $p = 0.002$; Bootstrap: $p = 0.008$, 95% CI [910.948, 2780.027]. Figure 6 depicts the progression for the different exploration actions separately (haptic scans, transfers, rotations). As can be seen from the graph, in general infants' reaction times decreased across the test blocks, suggesting that their anticipation became better synchronized with target appearance, independent of the manual exploration action. It is important that infants of the high haptic scan group showed a shorter reaction time compared to infants of the low haptic scan group. From the second test block onwards only the reaction times of the infants in the high haptic scan group were consistently below the cutoff time of 1,200 ms, and thus, predictive.

# Discussion

As previous results (Kubicek et al., 2017) have provided evidence of a positive link between 7-month-old infants' general manual object exploration behavior and their predictive looking to moving temporarily occluded objects, the present study investigated whether this relation also applies when 9-month-old infants reach for moving temporarily occluded objects. Specifically, we wanted to investigate whether there is a subset of procedures from the previously tested candidate procedures (haptic scans, transfers, rotations) that are particularly related to predictive grasping.

Similar to Kubicek et al. (2017), our results showed a significant link between 9-month-old infants' manual object exploration ability and their predictive reaching for objects. Thus, visual and manual anticipations seem to be based on similar processes, which in manual prediction seem to become visible in slightly older infants. However, while Kubicek et al. (2017) found visual prediction to be related to infants' general object exploration score, in our study (manual) predictive abilities were specifically related to infants' haptic scan score. We found that the prediction rate of the infants with a high haptic scan score was almost twice as high as that of the infants with a low haptic scan score. We found no comparable effects for the other manual exploration actions (transfers or rotations). Furthermore, we revealed a learning effect in terms of a general decrease of the reaction times across the four test blocks regardless of which exploration group (high vs. low) the infants belonged to. However, the reaction times of the infants of the high haptic scan group were

Downloaded from jov.arvojournals.org on 04/11/2021

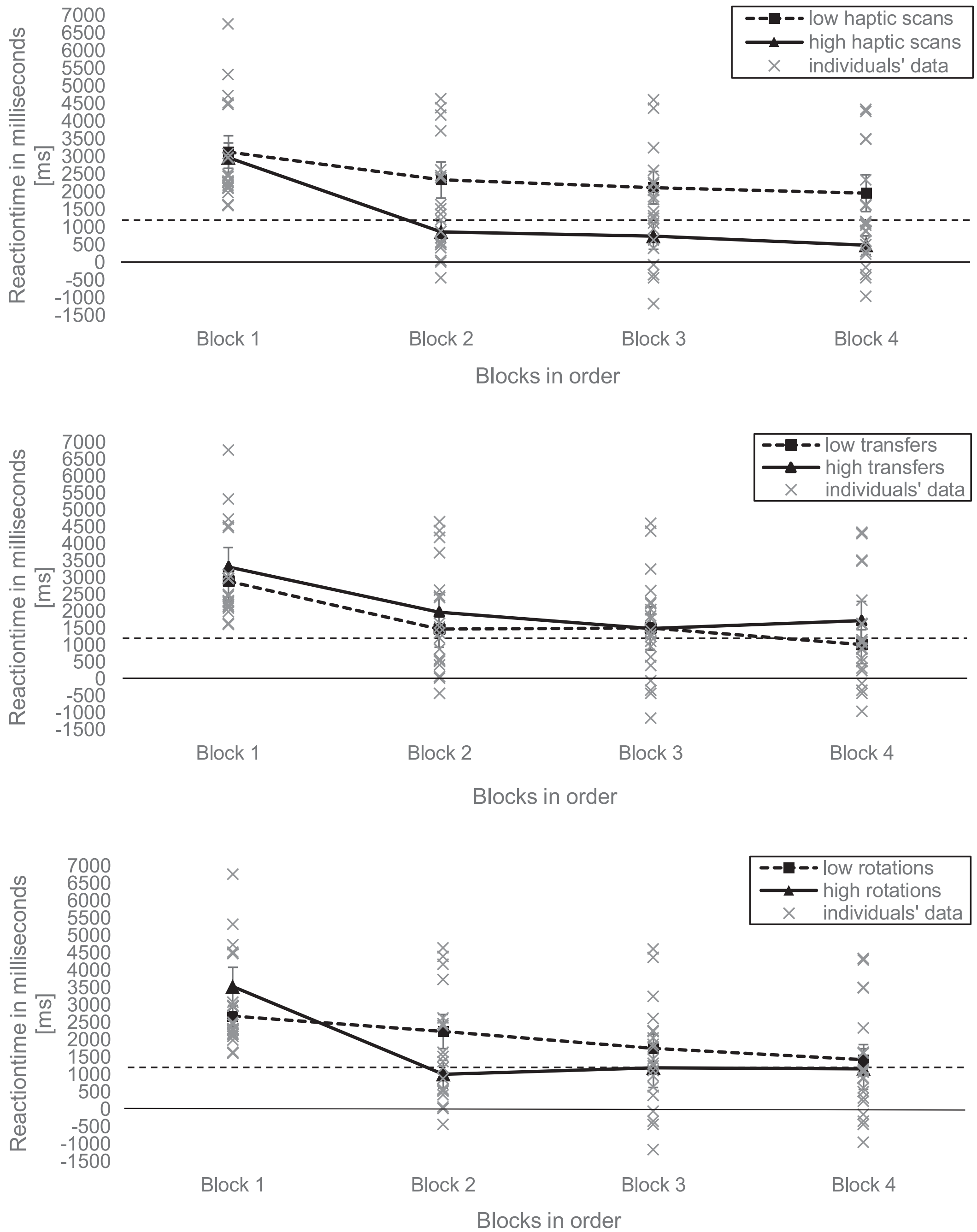


Figure 6. Reaction times in milliseconds (ms) during the four test blocks separately for the different exploration groups (haptic scans, transfers, rotations) and averaged data points within a block per infant. The discontinuous black lines represent the cutoff for predictive and reactive reaches at 1,200 ms. The continuous black lines at 0 ms represent the time point the object started to move. Error bars indicate the standard error of the mean. The scale reaches from −1,500 ms to 7,000 ms, because some infants started to reach before the object began to move. *Note*: There were significant differences between the first and the fourth test block as well as just a significant main effect for the general reaction time of the haptic scan groups. There were no interactions between test blocks and haptic scan group.

lower in general compared to infants in the low haptic scan group. This reflects the advantage for predictive grasping in this group.

With the exception that our study has found only a link between a specific exploration procedure (haptic scans) and manual prediction of a temporarily occluded object moving in space, it is consistent with several other studies on the relation between fine motor development and visual–spatial object processing in infants (e.g., Kubicek & Schwarzer, 2018; Schwarzer,

Downloaded from jov.arvojournals.org on 04/11/2021

2014). For example, Soska et al. (2010) demonstrated a relation between infants' general manual exploration skills and their ability of 3D object completion. While object completion is surely different from spatial prediction, one might argue that both tasks share their reliance on specific visual–spatial processes. Thus, object completion in terms of a mental representation of an unseen object part is very similar to predicting when a significant unseen part of a moving temporarily occluded object will reappear. Both require imagining object parts that are out of view for a certain time. According to the results, both are related to infants' manual object exploration skills, albeit to different manual skills. A similar agreement with our results can be seen in Schwarzer et al.'s (2013) study on infants' mental rotation ability. Here, 9-month-olds with a high general manual exploration score performed better in a mental rotation task than same-aged infants with a low exploration score (Schwarzer et al., 2013). Although visual–spatial skills in these studies were measured with a different paradigm, one could argue that the tasks share important internal visual–spatial processes, such as the mental representation of an object movement that has not been seen before. Again, these processes seem to be related to infants' manual object exploration skills, even if they are different.

As mentioned, in the present study it was one of the investigated manual exploration actions that particularly affected infants' performance in the manual prediction task, namely haptic scans. A possible explanation for the positive influence of haptic scans can be gained from an analysis of the information that can be gathered by employing this specific exploratory procedure. Specific manual exploratory procedures offer different information about an object's properties (Bushnell & Boudreau, 1993; Lederman & Klatzky, 1987). Regarding haptic scans, scanning an object with the fingers can help to perceive the contours of an object, which leads to an impression of its exact shape (Bushnell & Boudreau, 1993; Lederman & Klatzky, 1987; Soska et al., 2010). Correspondingly, one possible explanation why high haptic scanning infants performed better in the manual prediction task than low haptic scanning infants could be that these infants attended more strongly to the contours and shape of the object than the other group. This could have helped them to better anticipate the position of the different parts of the object during its movement.

Another possible explanation for the effects of haptic scans might be that they are particularly well suited for learning about the 3D structure of objects because they allow a simultaneous processing of an object's front and backside; that is, its spatial structure. One very salient feature of 3D objects is that they have backsides. The perception of the invisible backs of objects is critical for object recognition and the analysis of a scene (Soska et al., 2010). As an example, it has been shown that adults were better in solving an object recognition task if they had the opportunity to explore the back of the object with their hands than if they merely explored the objects' front (Newell, Ernst, Tjan, & Bülthoff, 2001). If infants hold an object in their hands while scanning it with their fingers, they have the possibility to perceive the front side visually and the back side haptically at the same time. A possible explanation why highly haptic scanning infants in our study showed a higher prediction rate than less haptic scanning infants is that they were able to represent the back of the object-array that the target objects were attached to. One may ask however, why especially haptic scans and not rotations were related to better performance in our predictive grasping task, because when you rotate an object you also gain knowledge about an object's backside. With regard to the exploratory procedure per se, it can be assumed that haptic scans provide a stronger connection between the visual and the haptic input compared to rotations. When you rotate an object you have to change your finger position faster, because you have to adapt the fingers to the new orientation of the object. During haptic scanning you can move the fingers on the back or front of the object and feel the surface of the other side simultaneously. Therefore, we assume that another crucial factor regarding haptic scans is that it results in a simultaneous haptic and visual impression of an object's front and back. The backside of an object is usually more accessible for the haptic system, whereas the front is more accessible for the visual system (Newell et al., 2001). Interestingly, Gerhard et al. (2018) also found a significant relation between haptic scans (fingerings) and the ability to differentiate 3D (real) objects and 2D images (pictures) of the same object. Seven-month-olds, who performed many haptic scans in an object exploration task, expressed a visual preference for 3D objects. On the contrary, same-aged low exploring infants showed no preference for the 3D or 2D object. The authors concluded that infants with a high haptic scan (fingering) score have an improved understanding of differences in object formats. Analogously, regarding the present study, it is possible that the infants with a high haptic scan score also had a better understanding of the three-dimensionality and hence a better processing of 3D objects and their spatial structures than infants of the other exploration groups.

Another possibility why especially haptic scans, but not transfers or rotations, influenced the ability to reach predictively is the different chronological emergence of these abilities during development. Haptic scanning is one of the first goal-directed exploration procedures used by infants. The ability to simultaneously touch and inspect an object emerges between 4 and 5 months of age (e.g., Rochat, 1989; Lobo,

Downloaded from jov.arvojournals.org on 04/11/2021

Kokkoni, de Campos, & Galloway, 2014). In contrast, infants begin to use rotations and transfers reliably only in the second half of the first year of life (Lobo et al., 2014). Accordingly, younger infants are very familiar with haptic scans to explore objects and know how to gain information by using this procedure.

Importantly, since the order of our tasks was randomized, we do not assume that infants have gained new knowledge about object properties within the manual exploration task, since there were no differences between infants who performed the manual exploration task before the visual prediction task and infants who did it after the visual prediction task. We assume that the infants who spontaneously showed many haptic scans in our manual exploration task also use this action most in their everyday life to explore objects. For this reason, we assume that these infants generally have a better understanding of object properties, which is, according to our results, positively related to their predictive grasping.

Our second finding was that regardless of performance in the manual exploration task, the reaction time of the infants improved over the four test blocks. Thus, results of the present study are partly in line with other studies that investigated improvements of predictive grasping over trials (e.g., Jonsson & von Hofsten, 2003). Whereas Jonsson and von Hofsten (2003) only reported an improvement (or recovery) in the dimming condition, there was no improvement of predictive reaching if they used an occluder. The authors explained this difference with an interference of the occluder and the reaching attempts. In more detail, they argued that there is a competitive representation of different objects. Thus, heightened attention to a new object like an occluder in a scene leads to a mitigation of target object representation. Although we also used an occluder for our manual prediction task, infants improved over trials. One possible explanation is that we did not use a second object for occlusion. Instead, the occluder was attached to the object array and thus, in a sense, was part of it. There was no need for the infants to get familiar with a new object. Thus, there was no conflict of attention between different objects. The set-up of the current study is probably more comparable to the dimming condition in Jonsson and von Hofsten's (2003) study. Another possible explanation is the fact that infants in our study did not see the objects' movement without any occlusion. Therefore, they did not have to recognize a second movement event, because they saw the same object throughout the whole task. During the blocks the infants steadily learned about the movement and the target objects' location of reappearance and improved their predictive grasping attempts. The learning effects are underscored by the result that infants' reaction times generally decreased after the first test block. Moreover, only infants of the high haptic scan group showed reaction times lower than 1,200 ms after the object began to move, which was our criterion to classify a grasping as predictive. This pattern supports the result that infants of the high haptic scan group had a higher prediction rate in general than infants of the low haptic scan group.

There are some limitations of the present study. First, the results of the present study cannot provide information on the developmental course of the relation between manual exploration skills (like haptic scan) and manual predictive abilities, because the age was held constant. For this case, a longitudinal study with younger infants should be a suitable solution. Second, we cannot specify which information gathered by haptic scans is the crucial factor for the positive relation to infants' predictive grasping. To tackle this question, different restrictions in the manual exploration task could be a possible solution. For example in different conditions the infants would only have the opportunity to explore the backside or the front of an object or both simultaneously. Furthermore, our results do not allow conclusions about a causal relation. It is possible that the ability to grasp predictively leads to more manual exploration actions in infants. Training studies would be appropriate to answer this question. One possibility to investigate the causal relation is to train the infants in predictive grasping and test them in a manual exploration task.

Our results show for the first time that there is a positive relation between 9-month-old infants' manual object exploration by haptic scans and their manual prediction of the time and location of reappearance of a moving temporarily occluded object. Information about objects gathered by haptic scans seems to facilitate the infants' understanding of object properties as well as object movements. Furthermore, this study shows that 9-month-old infants are able to improve their predictive grasping abilities during a test session.

*Keywords: manual object exploration, predictive grasping, occlusion*

## Acknowledgments

This study was supported through a grant from the Collaborative Research Center SFB/TRR 135/1 2014 at the German Research Foundation. The authors are indebted to the parents who donated their time to participate in the study with their infants. We are grateful to Ramona Schweizer and Lydia Jägersküpper for their assistance with data collection.

Commercial relationships: none.
Corresponding author: Gloria Gehb.

Downloaded from jov.arvojournals.org on 04/11/2021

Email: gloria.gehb@psychol.uni-giessen.de.
Address: Department of Developmental Psychology, Justus-Liebig-University Giessen, Giessen, Germany.

## References

Berkovits, I., Hancock, G. R., & Nevitt, J. (2000). Bootstrap resampling approaches for repeated measure designs: Relative robustness to sphericity and normality violations. *Educational and Psychological Measurement*, *60*, 877–892.

Bushnell, E. W., & Boudreau, J. P. (1993). Motor development and the mind: The potential role of motor abilities as a determinant of aspects of perceptual development. *Child Development*, *64*, 1005–1021, https://doi.org/10.1111/j.1467-8624.1993.tb04184.x.

Gerhard, T. M., Culham, J. C., & Schwarzer, G. (2018, March). *Visual preference for real objects over pictures is related to 7-month-old infants' manual object exploration*. Poster presented at the Tagung experimentell arbeitender Psychologen [Conference of Experimental Psychologist], Marburg, Germany.

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

Gredebäck, G., von Hofsten, C., & Boudreau, J. P. (2002). Infants' visual tracking of continuous circular motion under conditions of occlusion and non-occlusion. *Infant Behavior and Development*, *25*, 161–182, https://doi.org/10.1016/S0163-6383(02)00119-4.

Gredebäck, G., von Hofsten, C., Karlsson, J., & Aus, K. (2005). The development of two-dimensional tracking: A longitudinal study of circular pursuit. *Experimental Brain Research*, *163*, 204–213, https://doi.org/10.1007/s00221-004-2162-0.

Hespos, S., Gredebäck, G., von Hofsten, C., & Spelke, E. S. (2009). Occlusion is hard: Comparing predictive reaching for visible and hidden objects in infants and adults. *Cognitive Science*, *33*, 1483–1502, https://doi.org/10.1111/j.1551-6709.2009.01051.x.

Jonsson, B., & von Hofsten, C. (2003). Infants' ability to track and reach for temporarily occluded objects. *Developmental Science*, *6*, 86–99, https://doi.org/10.1111/1467-7687.00258.

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

Kubicek, C., & Schwarzer, G. (2018). On the relation between infants' spatial object processing and their motor skills. *Journal of Motor Learning and Development*, *6*(S1), S6–S23, https://doi.org/10.1123/jmld.2016-0062.

Lederman, S. J., & Klatzky, R. L. (1987). Hand movements: A window into haptic object recognition. *Cognitive Psychology*, *19*, 342–368, https://doi.org/10.1016/0010-0285(87)90008-9.

Lobo, M. A., Kokkoni, E., de Campos, A. C., & Galloway, J. C. (2014). Not just playing around: Infants' behaviors with objects reflect ability, constraints, and object properties. *Infant Behavior and Development*, *37*, 334–351, https://doi.org/10.1016/j.infbeh.2014.05.003.

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

Newell, F. N., Ernst, M. O., Tjan, B. S., & Bülthoff, H. H. (2001). Viewpoint dependence in visual and haptic object recognition. *Psychological Science*, *12*, 37–42, https://doi.org/10.1111/1467-9280.00307.

Rochat, P. (1989). Object manipulation and exploration in 2- to 5-month-old infants. *Developmental Psychology*, *25*, 871–884, https://doi.org/10.1037/0012-1649.25.6.871.

Rosander, K., & von Hofsten, C. (2004). Infants' emerging ability to represent occluded object motion. *Cognition*, *91*, 1–22, https://doi.org/10.1016/S0010-0277(03)00166-5.

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

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

Shepard, R. N., & Metzler, J. (1971, February 19). Mental rotation of three-dimensional objects. *Science*, *171*(3972), 701–703, https://doi.org/10.1126/science.171.3972.701.

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

Soska, K. C., Adolph, K. E., & Johnson, S. P. (2010).

Downloaded from jov.arvojournals.org on 04/11/2021

Systems in development: Motor skill acquisition facilitates three-dimensional object completion. *Developmental Psychology*, *46*, 129–138, https://doi.org/10.1037/a0014618.

Spelke, E. S., & von Hofsten, C. (2001). Predictive reaching for occluded objects by 6-month-old infants. *Journal of Cognition and Development*, *2*, 261–281, https://doi.org/10.1207/S15327647JCD0203_2.

van der Meer, A. L., van der Weel, F. R., & Lee, D. N. (1994). Prospective control in catching by infants. *Perception*, *23*, 287–302, https://doi.org/10.1068/p230287.

van Wermeskerken, M., van der Kamp, J., te Velde, A. F., Valero-Garcia, A. V., Hoozemans, M. J., & Savelsbergh, G. J. (2011). Anticipatory reaching of seven-to eleven-month-old infants in occlusion situations. *Infant Behavior and Development*, *34*, 45–54, https://doi.org/10.1016/j.infbeh.2010.09.005.

von Hofsten, C. (1980). Predictive reaching for moving objects by human infants. *Journal of Experimental Child Psychology*, *30*, 369–382, https://doi.org/10.1016/0022-0965(80)90043-0.

von Hofsten, C. V., Feng, Q., & Spelke, E. S. (2000). Object representation and predictive action in infancy. *Developmental Science*, *3*, 193–205, https://doi.org/10.1111/1467-7687.00113.

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

von Hofsten, C., & Rosander, K. (1997). Development of smooth pursuit tracking in young infants. *Vision Research*, *37*, 1799–1810, https://doi.org/10.1016/S0042-6989(96)00332-X.

von Hofsten, C., Vishton, P., Spelke, E. S., Feng, Q., & Rosander, K. (1998). Predictive action in infancy: Tracking and reaching for moving objects. *Cognition*, *67*, 255–285, https://doi.org/10.1016/S0010-0277(98)00029-8.

Wilcox, R. R. (2012). *Introduction of robust estimation and hypothesis testing* (3rd ed.). *Statistical modeling and decision science*. Amsterdam, Boston: Academic Press.

Woods, R. J., Wilcox, T., Armstrong, J., & Alexander, G. (2010). Infants' representations of three-dimensional occluded objects. *Infant Behavior and Development*, *33*, 663–671, https://doi.org/10.1016/j.infbeh.2010.09.002.

Downloaded from jov.arvojournals.org on 04/11/2021