INTRODUCTION

Planning prehension requires coordination between the perceptual and motor systems. The visual system must locate the object for retrieval and discern its critical features to guide the reach and grasp; the motor system must control the path of the moving arm and shape the hand to grasp, all the while maintaining balance and turning the torso and head to find the target. The problem of perceptual–motor coordination is exacerbated when body position is changing because passive forces due to motion act on the arms and body. Moreover, object position relative to the body changes, so the frame of reference must be continually updated. Coordinating perceptual and motor systems becomes even more challenging when the body is pivoting toward the object. If the turn begins with the object behind the body, the object’s location is initially unknown. So, perception and action must work in tandem to visually locate the object and plan prehension. Each new piece of perceptual information guides the next motor action, which in turn promotes gathering the next relevant piece of perceptual information (Gibson & Pick, 2000; Kretch & Adolph, 2017). In the current studies, we asked how infants and adults coordinate perception and action to retrieve objects while their bodies are passively pivoting; we used head-mounted eye tracking to observe the relative timing of visual and manual object prehension.

1.1 Planning prehension while the body is stationary

Dozens of studies report age-related changes in perceptual–motor coordination in the development of reaching (for reviews, see Adolph & Berger, 2006; Corbetta, 2009; von Hofsten, 2004). Perceptual–motor coordination is evident from the get-go: neonates extend their...
arms more frequently when an object is in view than when an object is not present (Amiel-Tison & Grenier, 1986; Lobo & Galloway, 2008; von Hofsten, 1982). By 3–4 months of age, infants execute their first visually guided reaches (e.g., Berthier & Keen, 2006). By 5–6 months, infants scale reaching to left-right locations relative to their own bodies. They use their right hand on the extreme right side of horizontal space and their left hand on the extreme left, but at locations around the body’s midline, they predominately use the right hand (Jacquet, Esseily, Rider, & Fagard, 2012; van Hof, van der Kamp, & Savelsbergh, 2002). For objects beyond arms’ reach to the side, infants turn their bodies to reach with the near hand (Bate & Thelen, 2004). For objects beyond arms’ reach to the front, infants lean forward as they extend an arm (McKenzie, Skouteris, Day, Hartman, & Yonas, 1993; Yonas & Hartman, 1993), and they refuse to reach if leaning forward would cause them to fall (Adolph, 2000).

When grasping a moving object, infants anticipate the object’s trajectory relative to their body and select the appropriate hand. They make proactive adjustments for the object’s expected location (von Hofsten, 1980, 1983). They “chase” the object with the near hand as it moves past or “catch” it with the far hand as it moves into the far side of reaching space (Fagard, Spelke, & von Hofsten, 2009). As object speed increases, infants switch from chasing to catching (von Hofsten, 1983). With age, the right hand becomes more efficient and successful at catching the moving target compared with the left hand (Fagard et al., 2009).

Despite a large literature on infant reaching, previous work focused on the development of visually guided object prehension with infants’ bodies in a stationary position. Regardless of whether the object was stationary or moving, the body’s frame of reference was fixed. The innovation in the current work is our focus on planning prehension while passively pivoting 180°, a task that demands ultrafast target localization and reach planning and continual updating about the body’s frame of reference.

### 1.2 Planning prehension while pivoting

Imagine sitting on a swivel chair with an object at an unknown location behind your back. Now your body is passively rotated toward the object. To grasp that object while your body is rotating—that is, prehension mid-turn while pivoting—you would need to quickly plan and execute a sequence of perceptual–motor behaviors. You would need to move your head and eyes to find the object, determine the hand currently closest to the object, and control the hand trajectory to grasp the object. All of this must occur within a few seconds while the chair turns and brings your body in line with the object.

Direction of rotation and object location will affect which hand is closer at the start of the turn and which hand is closer at the end of the turn. Thus, depending on object location, the hand that is closer can change as the turn commences. For example, while turning clockwise (to the right) with the object located on the right side of space, the right hand is always closer to the object. However, while turning clockwise with the object located on the left side of space, the right hand is initially closer at the start of the turn and the left hand becomes closer by the end of the turn. Prehension in both scenarios requires fast and efficient perceptual–motor coordination. However, the second scenario requires faster, more efficient planning for a right-handed grasp because the object needs to be captured before it becomes more easily available to the left hand. In some ways, the second scenario is analogous to chasing versus catching moving objects while the body is stationary. In other ways, however, it is very different. With a moving object and stationary body, the frame of reference is fixed; with a stationary object and a moving body, the perceptual frame of reference is changing. In addition, passive forces due to the rotational movement act on the body.

### 1.3 Pivot paradigm

We originally devised a “pivot paradigm” to study reaching across horizontal space under binocular and monocular viewing conditions (Ekberg et al., 2013). We needed several trials at each location to reliably determine reach scaling across left-right positions. Thus, we co-opted a swiveling method that we had used previously to garner dozens of trials from infants, children, and adults reaching through apertures (Ishak, Adolph, & Lin, 2008; Ishak, Franchak, & Adolph, 2014). Participants sat on a swiveling chair and were turned 180° toward the aperture apparatus; between trials, they were swiveled away while an assistant adjusted the apparatus. Infants and children found this game of turning back and forth to retrieve objects to be thrilling and happily produced 60+ trials (Ishak et al., 2014).

In the Ekberg et al. (2013) pivot paradigm, infants produced many reaches (36 trials over binocular and monocular viewing), and monocular viewing affected the timing of reach planning but not hand selection. However, we inadvertently discovered that infants quickly learned the game of turning to retrieve the targets and were so motivated that on some trials, they began reaching and occasionally retrieved the object before the chair had completed its full rotation. This behavior impressed us because it requires fast visual localization of the target, split-second decisions about reach planning, and control of the arm and hand while the frame of reference continually shifts.

Thus, the pivot paradigm may be a useful method for studying perceptual–motor coordination in ways not originally anticipated. Moreover, the pivot paradigm can be used with both infants and adults to characterize developmental change in the relative timing of perceptual–motor coordination for prehension. Our previous work (Ekberg et al., 2013) revealed that infants could plan reaches in this dynamic context, but the focus was on the effects of monocular/binocular viewing. So, infants’ ability to coordinate visual–manual actions during ongoing rotational changes in body position is still unknown. In addition, the relative timing of visual and manual actions for prehension while pivoting is unknown in both infants and adults. The current studies capitalized on the success of the pivot paradigm to study perceptual–motor coordination in infants and adults.

### 1.4 Current studies

In three studies, participants sat in an office swivel chair (infants on their caregiver’s lap). An experimenter turned them toward an upright
board with targets placed at various locations to the left and right of the board's center. The pivot paradigm provides precise and consistent changes in body position through experimentally induced passive rotation. The task of prehension while pivoting during active rotation would entail an overlapping set of perceptual–motor coordination skills and additional challenges to planning and control. Nonetheless, during passive rotation, participants must actively control eye, head, and arm movements. Moreover, because target location and turn direction changed on every trial, participants had to visually locate the target anew on each trial and plan the reach while accounting for ongoing changes in body position relative to target location.

In Experiment 1, we asked whether infants can plan and guide reaches while pivoting. And if so, do they scale mid-turn reaches to target location relative to turn direction? In Experiment 2, we used head-mounted eye tracking to examine the timing of infants’ manual actions relative to the acquisition of visual information. In Experiment 3, we tested a comparison group of adults and examined the relative timing of target visualization and arm movements using head-mounted eye tracking and high-speed motion tracking.

2 | EXPERIMENT 1: PREHENSION WHILE PIVOTING IN INFANTS

Experiment 1 tested infants’ ability to coordinate perceptual and motor systems quickly enough to prehend objects while pivoting. Previously, we discovered that 6- to 10-month-olds occasionally reach mid-turn (Ekberg et al., 2013). However, our previous work did not focus on mid-turn reaching, and infants received only 28 binocular reaching trials. Thus, in the current study, we increased the opportunity for mid-turn reaching to 60 trials per infant, and characterized prehension while pivoting across target location, turn direction, and age.

Our first aim was to quantify the frequency of mid-turn reaching. Our previous work used a relatively lenient criterion for labeling a reach as “mid-turn”—≤600 ms after the chair arrived at board center—and 22% of reaches were classified as mid-turn (Ekberg et al., 2013). Here, we adopted a more conservative criterion to ensure that only reaches that must have started while still pivoting were counted as mid-turn. We classified all reaches ending in target contact before the chair stopped at board center as mid-turn reaches. In addition, because it takes infants at least 300 ms to execute a reaching movement (Berthier & Keen, 2006; von Hofsten, 1983), we scored reaches with contact times ≤300 ms after the chair arrived at board center as mid-turn reaches because they must have begun while pivoting. We classified trials with contact times >300 ms after the chair arrived at board center as post-turn reaches. Our inclusion criterion for mid-turn reaches is likely conservative because infants could have begun to reach mid-turn but failed to contact the target within the 300-ms window. Thus, with the new criterion, mid-turn reaching would provide strong evidence of fast planning and efficient perceptual–motor coordination. Moreover, we determined the proportion of mid-turn reaches that were free of reach and grasp errors (e.g., striking the board during a reach or repositioning the hand after contact). Our previous study did not examine prehension errors during mid-turn reaches. Accuracy for reaching and grasping informs on how well mid-turn object retrieval was planned.

Our second aim was to document whether infants scale reaches to target location relative to turn direction because both factors must be continually tracked relative to current body position. Hand selection informs on scaling, because infants could reach with either hand at every location. However, whether the right or left hand was closer depended on turn direction, the current degree of chair rotation, and target location. The hand leading the turn was initially closer to targets on the near side of space (locations on the left during clockwise turns and locations on the right during counterclockwise turns), but as the chair approaches board center and the leading hand passes the target, now the previous trailing hand is closer and the former leading hand would have to cross over the body’s midline to retrieve the target. For targets on the far side of space (locations on the right during clockwise turns and locations on the left during counterclockwise turns), the leading hand was always closer than the trailing hand and would never have to cross the body’s midline (see Figure 2).

Our previous work did not find age differences among 6-, 8-, and 10-month-olds in the frequency of mid-turn reaches (Ekberg et al., 2013). So here we sampled across the same age range tested previously, plus older infants—6 to 15 months. The wide cross-sectional sample did not allow us to examine the shape of developmental change, but it did allow us to determine whether mid-turn reaching changes with age.

2.1 | Method

2.1.1 | Participants

We tested 41 infants (15 girls, 26 boys) from 6 to 15 months of age (Figure 1: open bars). Families were recruited from maternity wards of local hospitals in the New York City area and received photographs and diplomas as souvenirs of participation. Data from an additional 20 infants were not analyzed due to equipment failure (n = 3), experimenter error (n = 2), parental interference (n = 1), fussiness (n = 6), or refusal to retrieve targets on more than 25% of trials (n = 8).

2.1.2 | Materials and procedure

Figure 2a shows the reaching apparatus and procedure. Infants reached for small toy targets (<3 cm in diameter) placed at 15 prespecified intervals across the horizontal reaching space in 4-cm increments 0 to 28 cm to the left (negative numbers in figures and text) and right (positive numbers in figures and text) of board center. Magnets affixed to the back of each toy allowed easy placement and removal from an upright magnetic whiteboard (60.6 cm × 90.8 cm). To produce enough data to analyze data in both turn directions, we collapsed the 15 object locations into bins to the left of board center, around board center, and to the right of
board center: −24 cm (−28 to −20 cm), −12 cm (−16 to −8 cm), 0 cm or board center (−4 to +4 cm), +12 cm (+8 to +16 cm), and + 24 cm (+20 to +28 cm).

Infants sat on their caregiver’s lap in a pivoting office chair in front of the board. Before starting the experiment, an experimenter adjusted chair height to maintain targets at infants’ chest level, aligned the center of the chair with the 0 cm (board center) target location, and moved the chair forward or backward to keep the target locations within infants’ partially extended arms’ length. We chose a flat surface rather than a curved one so that infants had the potential to miss the target with the leading hand while mid-turn: That is, infants could not simply leave their hand up and knock the toy off the apparatus. A warm-up period of 3–4 pivot trials taught infants the game of spinning toward the board.

At the start of each trial, the chair (and thus infant and caregiver) faced away from the board toward an assistant (pictured in Figure 2a). A computer operator (out of infants’ sight) ran a customized software program that specified target location in a random order, blocked within sets of 15 trials. We randomized target location to avoid trial order effects. The operator displayed the appropriate increment on a monitor visible to the experimenter, unseen by infants, who placed the target on the board. Infants’ hands began each trial down and close to their laps. Then, the experimenter spun the chair 180° (at approximately 50°/s) and stopped spinning the chair when it was parallel to the board with the infants’ chest at board center. Turn direction alternated between trials: Clockwise turns resulted in infants’ right hand leading the approach to the board and counterclockwise turns resulted in infants’ left hand leading the approach. After each trial, the experimenter turned the chair back toward the assistant and the assistant gently removed toys from infants’ hands. We instructed caregivers to tuck their legs under the chair and to shut their eyes during the trials to limit their influence on infant’s actions. Infants quickly learned the game of pivoting to retrieve targets. We attempted to run 60 trials with each infant. Some tolerated 60+ trials (23 infants), but every infant received at least 30 test trials ($M = 55.8$ trials) before...
fussing or losing interest in the task. The pivot paradigm lasted approximately 20 min.

Three digital cameras recorded infants’ actions. One camera, suspended above the board, recorded an overhead view. A second camera, on one side of the pivot chair, recorded infants’ entire body to determine when they faced the center of the board. A third camera recorded a close-up view of infants’ arm and hand movements during the approach toward the target. The three camera views were mixed with the computer display of target location into a single video for later coding.

2.1.3 | Data coding

A primary coder used Datavyu (www.datavyu.org), an open source, computerized video coding tool, to identify mid-turn reaches based on contact time, identify reach and grasp errors, and determine hand selection. A second coder scored 25% of each infant’s data. The correlation coefficient for contact time was 0.99, coders agreed on 97.0% of trials for reach and grasp errors ($\kappa = 0.94, p < 0.001$), and interobserver reliability for hand selection was 98.5% ($\kappa = 0.97, p < 0.001$).

Contact time began when infants were at board center facing the board and ended when their hand contacted the target. Because infants could begin reaching before the chair stopped at board center, contact time could be negative (contacted target before chair stopped at board center) or positive (contacted target after chair stopped at board center). Based on our 300-ms criterion (minimum time to execute a reach), we classified reaches with contact times $\leq 300$ ms as mid-turn reaches and those $>300$ ms as post-turn reaches. The primary coder scored reach onset from video on trials with contact times between 0 and 3 s. Scoring reach onset proved difficult: Coders agreed within one frame on only 54.6% of trials. However, we did find 100% agreement on whether a reaching movement began before the chair reached board center. That is, this coding verified that all reaches identified as mid-turn based on our 300-ms cutoff contained a reaching movement that started before the chair arrived at board center.

The coder scored reach and grasp errors if infants struck the apparatus with their reaching hand before contacting the target, repositioned their hand before removing the target from the board, switched hands between initial contact and object retrieval, or failed to remove the target from the board. Hand selection was scored as the first hand to contact the target. Bimanual reaches (both hands touched within 0.5 s) were rare ($M = 0.03$% of trials), so they were excluded from analyses.

2.2 | Results

Although infants received 31–65 trials in total ($M = 55.8$), they did not attempt to reach on 5.1% of trials in the dataset ($M = 2.83$ per infant, $SD = 3.88$). On an additional 11.1% of trials ($M = 6.20$ per infant, $SD = 5.62$), they waited several seconds to contact the target after the chair arrived at board center (5–28 s); on these “long” trials, infants appeared distracted. Thus, we excluded trials with contact times $>5$ s. Final analyses included 21–61 useable trials per infant ($M = 48.1$) and the number of useable trials increased with age, $r(39) = 0.43, p = 0.004$. Preliminary analyses showed no effects due to sex or number of trials and no change across the session.

2.2.1 | Mid-turn reaching and errors

With the 300-ms criterion, a substantial proportion of reaches (33.5%) occurred mid-turn. Infants displayed $M = 16.4$ mid-turn reaches ($SD = 10.9$), and every infant produced at least one mid-turn reach. Overall infants produced more mid-turn reaches than in our previous work (22%) that used a more lenient 600-ms criterion (Ekberg et al., 2013), but when we analyzed only the data from 6- to 10-month-olds (the ages observed in the previous study), we found a similar percent of mid-turn reaches (21.7%). In contrast to our previous study in which the overall prevalence of mid-turn reaching did not increase with age (Ekberg et al., 2013), here we found that the percent of trials with mid-turn reaches increased with age, $r(39) = 0.49, p = 0.001$ (circles in Figure 3a). However, we found no relation with age when analyzing only the 6- to 10-month-old age group, as in our previous work, $r(15) = 0.30, p = 0.24$.

Overall, 24% of all reaches occurred mid-turn with no errors in the reach or grasp. Infants displayed $M = 11.7$ error-free mid-turn reaches ($SD = 9.2$). Error-free mid-turn reaching also increased with age, $r(39) = 0.59, p < 0.001$ (Figure 3b), and error-free mid-turn reaches increased across the 6- to 10-month age interval, $r(15) = 0.53, p = 0.03$. (a) Mid-turn reaches and (b) error-free mid-turn reaches. Circles denote infants in Experiment 1, crosses denote infants in Experiment 2, and triangles denote adults in Experiment 3.
2.2.2 | Scaling manual actions while pivoting

To determine whether infants scaled their hand selection during mid-turn reaching, we included turn direction and object location as fixed-effect factors in a generalized estimating equation (GEE). We also included age as a continuous covariate to examine effects of turn direction and object location while statistically controlling for age at testing (data were centered on the mean age of the sample, 10.43 months). In addition, in the same model, we could explore how scaling of manual actions covaried with age overall and across the fixed-effect factors. We used a GEE approach rather than traditional analyses of variance, because infants’ useable trials were not distributed evenly across target locations and performance at each location was likely not independent of performance at other locations. After determining the best model fit (based on goodness of fit of QIC), we used a normal distribution with an identity link and AR(1) covariance structure, with the total number of useable trials as a scale weight factor at each object location. Main effects and interactions for the GEE are presented in Table 1. We used Sidak corrections for multiple comparisons.

Indeed, as shown by the main effect for turn direction in Table 1 and the disparity between leading and trailing hands in Figure 4a, infants scaled hand selection to turn direction. In both turn directions, infants sometimes brought their leading hand up early enough to contact targets on the far side of reaching space (−24 cm bin for clockwise turns and +24 cm bin for counterclockwise turns), but they most frequently contacted targets with their trailing hand as they turned in.

Importantly, use of the leading hand was attuned to object location relative to turn direction (see object location × turn direction interaction in Table 1 and switch between leading and trailing hands in Figure 4a). Follow-up comparisons revealed that while turning clockwise, use of the leading right hand significantly increased from the −24 cm to the −12 cm bin and from the −12 cm to board center bin (ps < 0.001); leading right hand use remained comparably high at the +12 cm and +24 cm bins (ps > 0.40). While turning counterclockwise, use of the leading left hand increased significantly at the board center bin relative to the +12 cm and +24 cm bins (ps < 0.001), further increased at the −12 cm bin (p = 0.005), and remained comparably frequent at the −24 cm bin (p = 0.99).

Moreover, leading hand use began increasing at locations closer to infants’ approaching bodies when turning clockwise (right hand leading) compared to turning counterclockwise (left hand leading). While being turned clockwise, infants used their leading right hand on M = 52.3% of targets on the nearer, left side of board center and M = 94.9% of targets on the right side. In contrast, while being turned counterclockwise, infants used their leading left hand to contact M = 25% of targets on the nearer, right side of board center and M = 66.8% of targets on the left side of space. Infants accounted for turn direction and quickly calibrated hand selection to use the leading hand; yet turning clockwise, with the right hand leading, bore an advantage for mid-turn reach frequency.

With age, frequency of leading hand use did not increase overall (no main effect of age in Table 1) but rather did so at specific locations for specific directions (age × location and age × location × direction interactions in Table 1). Decomposing the age × location interaction, infants deployed more leading hand reaches at locations nearer to their approaching turn (±24 and ±12 cm bins) with increasing age, βs > 0.11, ps < 0.001. That is, with age, infants displayed more mid-turn reaches with their leading hand on the near side of reaching space compared to board center or locations farther from the turning body. Decomposing the three-way interaction, this effect was more dramatic while turning clockwise (with the right hand leading), βs > 0.14, ps < 0.001, compared to counterclockwise. Indeed, mid-turn reaching with the right hand leading was more prevalent overall and subsequently improved the most across age.

2.2.3 | Scaling manual actions while stationary

For post-turn reaches that occurred after the chair arrived at board center, the GEE showed no effect of turn direction (Wald χ² = 1.89, p = 0.17) on hand selection, but a main effect of object location (Wald χ² = 428.72, p = 0.011). Infants neatly scaled hand selection to target location by choosing the hand closer to the target after the chair stopped moving.

2.3 | Discussion

Although 2- to 3-month-olds demonstrate the perceptual-motor coordination for visually guided reaching (von Hofsten, 1982, 1984), reaching in the midst of a turn is far more challenging. In the current study, infants showed evidence of mid-turn reaching by 6 months of age. But mid-turn reaches for 6- to 10-month-olds often contained reach or grasp errors. Error-free mid-turn reaching increased steadily between 6 and 16 months. Apparently, what changes with age is the ability to accurately plan the entire sequence of visual-manual actions.

During mid-turn reaching, infants tailored hand selection to target location relative to turn direction. Infants increased use

### Table 1: Experiment 1 main effects and interactions with fixed effects (object location, turn direction) and age as a covariate in the GEE on leading hand use for mid-turn reaches

<table>
<thead>
<tr>
<th>Independent Measures</th>
<th>Wald χ²</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turn direction</td>
<td>10.83</td>
<td>0.001</td>
</tr>
<tr>
<td>Object location</td>
<td>10.67</td>
<td>0.031</td>
</tr>
<tr>
<td>Turn direction × object location</td>
<td>227.43</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Age</td>
<td>1.96</td>
<td>0.16</td>
</tr>
<tr>
<td>Age × turn direction</td>
<td>0.59</td>
<td>0.44</td>
</tr>
<tr>
<td>Age × object location</td>
<td>10.40</td>
<td>0.034</td>
</tr>
<tr>
<td>Age × turn direction × object location</td>
<td>16.46</td>
<td>0.002</td>
</tr>
</tbody>
</table>
of the leading hand for object locations farther from their turning bodies. In addition, they even scaled hand selection in cases when the leading hand would become the trailing hand after the chair reached board center—for example, target on the left side of space during a clockwise turn (see −12 cm bin in Figure 4a). In contrast, post-turn reaches neatly scaled to object location alone, as expected from previous work (Gabbard, Helbig, & Gentry, 2001; Jacquet et al., 2012). The greatest age-related improvements for mid-turn reaching occurred on the near side of space, where prehension requires faster perceptual–motor coordination. Accordingly, near-side reaches were more frequent in older infants. Consistent with other studies, infants displayed an overall right hand advantage (Morange & Bloch, 1996; Morange-Majoux, Peze, & Bloch, 2000), with more frequent mid-turn reaches with the right hand as it led the turn compared to when the left hand led the turn. This right side advantage increased with age, but likely only reflects a group effect because previous work found individual differences in early right- and left-side lateralization (Michel, Tyler, Ferre, & Sheu, 2006; Nelson, Campbell, & Michel, 2013).

Even the youngest infants in our sample (6- to 8-month-olds) demonstrated flexible perceptual–motor planning beyond that shown in previous work on infant reaching. Experiment 2 aimed to describe the timing of relevant visual input for planning prehension in the pivot paradigm in the youngest age group.

3 | EXPERIMENT 2: SEEING AND PREHENDING THE TARGET WHILE PIVOTING IN INFANTS

Experiment 2 addressed two key questions. First, what is the rate-limiting factor for prehension while pivoting? Possibly, seeing the target in the periphery sets off the necessary manual actions for prehension. If so, the target should come into infants’ field of view earlier on trials with mid-turn reaching—where infants contact the target earlier—compared to trials with post-turn reaching—where they contact the target later. Although passively rotated, infants can control when the target comes into their field of view by actively turning their head and torso. However, if infants show no differences in relative timing of the target coming into view between mid- and post-turn reaches, then seeing the target’s location in the periphery is not the bottleneck.

Second, is there a prescribed sequence of visual–manual actions (e.g., target comes into view, then infants fixate the target, then infants lift the hand, and finally hand contacts the target) during prehension while pivoting? Or can some behaviors happen in other orders or not at all? Obviously, the target must be in infants’ field of view to know its location relative to the body. However, infants may not need to fixate the target prior to contact (Corbetta, Thurman, Wiener, Guan, & Williams, 2014). As in other visually guided actions.
such as walking (Franchak & Adolph, 2010), infants might plan mid-turn reaching via peripheral vision. Indeed, the reach could start before or after the target comes into view.

In Experiment 2, we used head-mounted eye tracking to determine when the target appeared in view relative to starting the reach, and if and when infants fixated the target prior to contact. The eye tracker’s scene camera is the best proxy we had of when the target came into infants’ peripheral view. The sample size in Experiment 2 was small, but eye-tracking data provided a wealth of information on gaze dynamics to allow time-series analysis for each trial.

3.1 Method

3.1.1 Participants

Five infants (3 girls, 2 boys) from 6 to 8 months of age (Figure 1, striped bars), were recruited and compensated as in Experiment 1. Data were excluded from seven additional infants due to fussiness (n = 5), parental interference (n = 1), and equipment failure (n = 1). Eye-tracking data were collected but not analyzed from seven other infants due to poor calibration of the eye tracker (n = 3) and lost calibration due to infants pulling the eye tracker (n = 4).

3.1.2 Reaching apparatus and procedure

The apparatus and task were similar to Experiment 1 (Figure 2a). We used fewer target locations to obtain more data at every target location. Infants reached for toy targets placed at three locations across the horizontal reaching space—board center, 20 cm to the left, and 20 cm to the right of board center. A computer operator ran a customized software program that specified target location in a random order, blocked within sets of 12 trials. Turn direction (clockwise and counterclockwise) was also randomized across trials. The experimenter gave infants 5 s to store the target before turning the chair back toward the assistant. Infants received 25–57 test trials (M = 37.4 trials). Sessions lasted approximately 40 min.

3.1.3 Head-mounted eye tracking

Infants wore a Positive Science (positivescience.com) head-mounted eye tracker (Figure 2b). The tracker consisted of two small cameras mounted on lightweight headgear: the scene camera pointed outward from above the right eye to record the scene, and the eye camera pointed inward to record the infant’s eye. The scene camera field of view was 54.4° horizontal  ×  42.2° vertical. The headgear was a flexible band attached to the front of a spandex cap.

After placing the cap and headgear on the infants, an assistant called infants’ attention to locations on a display board, by presenting noisy toys in cutout windows, to calibrate the eye tracker. We used a minimum of 4 calibration points spread out over the entire scene camera field of view. Videos from both cameras recorded at 30 fps. We used Yarbus software to calculate the point of gaze (spatial accuracy ~2°) superimposed within the scene camera video (Franchak, Kretch, Soska, & Adolph, 2011). Videos from the eye tracker were synchronized with videos of infant reaching and mixed into a single frame for offline coding.

3.1.4 Data coding

As in Experiment 1, a primary coder scored contact time, hand selection, and reach/grasp errors from video. Using eye-tracking videos, the coder identified when the target came in view (first frame a pixel of the target appeared at the scene camera’s edge) and used the location of the gaze cursor to then score if and when infants fixated the target (when the gaze cursor was on the target for ≥3 consecutive frames). A second coder scored 20% of each infant’s data to ensure interobserver reliability. The correlation coefficient for contact time was 1.0, agreement for hand selection was 100% (κ = 1, p < 0.001), and agreement was 94.3% for reach and grasp errors (κ = 0.84, p < 0.001). Only one bimanual reach occurred in Experiment 2, and so was excluded from analyses. Coders agreed on 94.4% of trials for whether infants fixated the target (κ = 0.90, p < 0.001), and the correlation coefficient for time to fixate was 0.99. On 11.7% of trials, the software lost the eye track, so these trials were removed from analyses involving fixations, but not from analyses involving when the target appeared in view.

Because we aimed to characterize the relative timing of visual and manual actions, a coder also identified reach onset based on when the hand or arm that eventually contacted the target began to move. This time proved difficult to identify reliably. A second coder scored reach onset on every trial for all infants, but interobserver agreement (within 1 video frame or 33 ms) was only 56.4%. So analyses involving reach onset only included the trials with interobserver agreement within one frame.

3.2 Results

We identified trials with usable reaches based on the same criteria as in Experiment 1. On 4.3% of trials, infants did not attempt to reach; on an additional 12.3% of trials, they waited 5+ seconds to contact the target after the chair arrived at board center. Thus, analyses included only 23–40 trials per infant (M = 32.6)–163 trials in total. Due to the small sample size, we pooled reaches across infants for analyses, following previous conventions (Clifton, Rochat, Robin, & Berthier, 1994; Franchak et al., 2011; von Hofsten & Ronnqvist, 1988). Preliminary analyses showed no effects due to sex or number of trials or change across the session.

3.2.1 Mid-turn reaching and errors

As in Experiment 1, most reaches made contact shortly before or just after the chair arrived at board center. Based on our 300-ms criterion for mid-turn reaching, 41 reaches (25.2% of all reaches) were mid-turn—comparable to infants in the same age range in Experiment 1 (17.9%). Infants produced M = 8.0 mid-turn reaches (SD = 9.3), similar to same-aged infants in Experiment 1 (M = 7.0, p < 0.001).
SD = 3.2), t(11) = 0.42, p = 0.69 (Figure 3a: crosses vs. circles). As shown in Figure 3a, the oldest infant in Experiment 2 produced a greater percent of mid-turn reaches compared to the other infants, but as shown in Figure 3b, his error-free mid-turn reaches were aligned with the other infants.

Pooled across infants, 10% of reaches occurred mid-turn and were error-free. Four infants produced at least one error-free mid-turn reach, ranging from 1–8, M = 3.0 (SD = 2.9). The proportion of error-free mid-turn reaches was similar to those in Experiment 1 (M = 3.0, SD = 2.6) in same-aged infants, t(11) = 0.21, p = 0.84 (Figure 3b, compare crosses and open circles).

3.2.2 Scaling of manual actions

As in Experiment 1, infants scaled mid-turn reaches to target location and turn direction and post-turn reaches only to target location. Because of the pooled sample and fewer target locations in Experiment 2, we used Chi-square tests to assess scaling effects. For mid-turn reaches, infants used progressively more leading, right hand reaches when the target was located further to the right when turning clockwise, χ²(1) = 8.00, p = 0.005 and leaving, left hand reaches when the target was located further to the left when turning counterclockwise, χ²(1) = 11.53, p = 0.003. For post-turn reaches, turn direction did not reliably affect hand selection in either turn direction, χ²(1) < 0.7, ps > 0.4; infants scaled hand selection to target location, χ²(1) = 46.40, p < 0.001, with right hand use progressively increasing from 5/38 trials (13%) at the left side locations to 37/42 trials (88%) for the right side locations.

3.2.3 Timing of visual and manual object retrieval

The critical data concern the relative timing among visual and manual events. For mid-turn reaches (Table 2 top and Figure 5a), the target appeared in view significantly earlier than the chair arrived at board center. The target came into view nearly simultaneously with reach onset but significantly before contact time. In fact, during mid-turn reaches, infants sometimes started reaching before the target appeared in the scene camera view (34.8% of trials). We found no differences in the timing of seeing the target for error-free reaches and reaches with reach or grasp errors, p > 0.10. For mid-turn reaches, infants fixated the target on 58% of trials and fixations happened significantly after the target came into view, and significantly after reach onset. Most fixations occurred nearly simultaneously with contact time (see Figure 5a), and 19% of fixations occurred after target contact. We found no differences in the frequency of fixations and relative timing of fixations for error-free reaches and reaches with reach/grasp errors, ps > 0.10.

Post-turn reaches (Table 2 bottom and Figure 5b) showed a similar relative timing of visual–manual actions, but the target came into view later compared to mid-turn reaches. For post-turn reaches, the target appeared in view almost simultaneously with the chair arriving at board center and significantly before reach onset. In addition, infants rarely started reaching before the target came into the scene camera view (0.12% of trials). However, the time to execute the reach (contact time relative to reach onset) was similar for post-turn and mid-turn reaches. Infants fixated the target on 58% of post-turn reaches, χ²(1) = 0.003, p = 0.96, and fixations happened significantly after the target came in view, which is a significantly longer delay compared to mid-turn reaches (Table 2 and Figure 5). During post-turn reaches, fixations occurred significantly after reach onset and significantly before contact times, but both of these relative timings were similar to mid-turn reaches. Altogether, there is a greater delay between the target coming into view and starting the reach or fixating the target for post-turn relative to mid-turn reaches.

<table>
<thead>
<tr>
<th></th>
<th>Target in view</th>
<th>Reach onset</th>
<th>Fixates target</th>
<th>Contact time</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mid-turn</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reach onset</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fixates target</td>
<td>0.68**</td>
<td>0.82*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contact time</td>
<td>0.87**</td>
<td>0.79**</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td>Chair board center</td>
<td>0.97**</td>
<td>0.84**</td>
<td>0.34</td>
<td>0.97</td>
</tr>
<tr>
<td><strong>Post-turn</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reach onset</td>
<td>0.97**</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fixates target</td>
<td>1.22**</td>
<td>0.54*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contact time</td>
<td>1.65**</td>
<td>0.84**</td>
<td>0.45*</td>
<td></td>
</tr>
<tr>
<td>Chair board center</td>
<td>0.02</td>
<td>-1.01**</td>
<td>-1.13**</td>
<td>-1.67**</td>
</tr>
</tbody>
</table>

Note. Reading down each column, each cell in the table reflects the difference in timing (in seconds) between the event in the top row and the event in the left column. Negative values indicate the left column event occurred before the event in the top row. Asterisks indicate values that are significantly different from 0 based on within-sample t tests. Bold indicates values that are significantly different between mid- and post-turn reaches based on between-sample t tests. *p < 0.05, **p < 0.01.
Experiment 2 for (a) mid-turn and (b) post-turn reaches. Negative numbers are times before the chair arrived at board center; positive numbers are times after the chair arrived at board center (denoted by 0 s) for infants in Experiment 2.

Vertical lines in each box represent the median time for that action. The width of the box represents the bounds of the 25th–75th percentiles of times for that action. The ends of the whisker lines represent the minimum and maximum times for that action.

FIGURE 5 Timing of visual and manual actions relative to when the chair arrived at board center (denoted by 0 s) for infants in Experiment 2 for (a) mid-turn and (b) post-turn reaches.

3.3 | Discussion

What is the bottleneck for mid-turn reaching? The target appeared in the field of view on 100% of the trials by the time target contact occurred in both mid- and post-turn reaches—indeed, no reaches involved serendipitous contact by simply holding a hand up as the chair spun around. Fixations, however, were not required to plan and guide prehension. Infants fixated the target before hand contact on only 39% of mid- and post-turn reaches; and on 19% of reaches, they fixated the target after hand contact. As in previous work (Corbetta et al., 2014; Franchak & Adolph, 2010), infants often use visual information from the periphery to plan and guide reaches. Because infants’ field of view (180° wide; Mayer, Fulton, & Cummings, 1988) is larger than the scene camera’s field of view (54.4° wide), targets likely appeared in infants’ periphery earlier than we report here. Nevertheless, we could determine the relations between when the target came into view (a proxy of seeing the target in the periphery) and reach timing.

The key finding was that on mid-turn reaches infants demonstrated faster visual information gathering than on post-turn reaches. For mid-turn reaches, the target came into view a second before the chair arrived at board center. In contrast, for post-turn reaches, the target came into view almost simultaneously with the chair arriving at board center. Thus, the critical difference between mid- and post-turn reaches was when the target appeared in the field of view—likely by infants turning their head and eyes faster than the chair pivoted. To our surprise, bringing the target into view earlier or fixing the target did not affect performance (error-free vs. non-error-free) for mid- or post-turn reaches.

Does prehension require a consistent sequence of visual–manual actions? It does not. Infants started reaching at any time relative to when the target came into view—planning hand selection with minimal visual information from the periphery, or only after the target was in view for several seconds. They could fixate before, during, or after hand contact, or not at all. Yet, we did see evidence of efficient and tightly coupled perceptual–motor coordination for mid-turn but not post-turn reaches.

In summary, Experiment 2 showed that by 6 months of age, infants consistently use peripheral visual information during prehension in the pivot paradigm. In addition, mid-turn reaches are characterized by tight coordination between visual and manual actions. Experiment 3 used eye tracking and motion tracking to describe the timing of visual input and reaching performance in adults as a benchmark against which to consider infant perceptual–motor coordination.

4 | EXPERIMENT 3: SEEING AND PREHENDING THE TARGET WHILE PIVOTING IN ADULTS

Adults are adept at planning and guiding reaches using visual information, even while their body is moving. They actively search for the target by moving their head and eyes (Land & Hayhoe, 2001). Moreover, eye-in-head behaviors are tightly linked to active or passive trunk rotation and compensate for shifts in the frame of reference (Land, 2004). To guide reaching movements, adults fixate the target during ongoing body movement or quickly after they stop moving (Land & Hayhoe, 2001; Land, Mennie, & Rusted, 1999). When their bodies are passively rotated while reaching, adults stabilize their torso to seamlessly support prehension (Bortolami, Pigeon, DiZio, & Lackner, 2008; Pigeon, Bortolami, DiZio, & Lackner, 2003a, 2003b).

Previous work, however, only describes piecemeal components in adult mid-turn reaches. Thus, in Experiment 3, we characterized the full visual–manual cascade in the mature perceptual–motor system in the pivot paradigm. We used head-mounted eye tracking and motion tracking to examine the relative timing of when the target came into view, starting to reach, fixating the target, and contacting the target. The motion tracker also allowed us to compare the kinematics (e.g., duration, speed) of mid- and post-turn reaching.

4.1 | Method

4.1.1 | Participants

Thirteen young adults (8 women, 5 men), \( M = 27.9 \) years of age (SD = 7.5 years), were recruited through word of mouth. All had normal vision and self-reported right hand dominance. Data from 11 additional adults were excluded due to equipment failure (\( n = 1 \)) or issues that prevented synchronization among data streams (\( n = 10 \)).
4.1.2 Reaching apparatus and procedure

The apparatus and task were similar to Experiments 1 and 2. However, the experimenter instructed adults to retrieve targets as quickly as possible. Adults sat on a swiveling office chair and reached for small targets affixed with Velcro to a wooden board. Targets were located at board center (0 cm) and at 20, 40, 60, 80, 100, and 120 cm to the left (negative numbers in Figure 4 and text) and right (positive numbers in Figure 4 and text) of board center. Targets were placed at farther distances to account for adults’ longer arms. Data were collapsed into 7 bins: −110 cm (−100 to −120 cm), −70 cm (−60 to −80 cm), −30 cm (−20 to −40 cm), 0 cm (board center), 30 cm (20 to 40 cm), 70 cm (60 to 80 cm), and 110 cm (100 to 120 cm).

As in Experiments 1 and 2, a computer operator (out of participants’ sight) ran a customized software program that specified target locations in a random order blocked within sets of 15 trials. Participants received M = 59.2 trials. Turn direction (clockwise and counterclockwise) was randomized between trials, and the experimenter spun the chair at approximately 60°/s. To ensure vigilance and to keep the task surprising and challenging for adults, no target was placed on M = 7 trials (SD = 2.3).

4.1.3 Equipment

Adults wore a Positive Science head-mounted eye tracker (attached to an adult-sized eyeglass frame; Franchak et al., 2011) and Ascension motion tracking markers. We calibrated the eye tracker using nine points. Participants kept their heads still and moved only their eyes to spread the calibration points over the field of view. Magnetic motion tracking (3D Guidance trackSTAR, Ascension Technology) recorded the chair rotation (sensor placed at the middle chair back) and movements of both arms (sensors placed on the styloid process of the radius, i.e., the wrist) at 240 Hz.

A video camera above the reaching apparatus recorded the entire scene. Reaching and eye-tracking videos were synchronized and mixed into a single frame for offline coding. A light emitting diode (LED) connected to the motion tracker was flashed at the beginning of the experiment and recorded in the scene camera of the eye tracker and third-person overhead video to synchronize video and motion-tracking data.

4.1.4 Data coding

As in Experiments 1 and 2, a primary coder scored videos for contact time, hand selection, errors, when the target came into view, and if and when participants fixated the target. Similar to Experiment 2, adults’ peripheral vision was larger than that of the scene camera, thus the scene camera likely underestimated how soon the target came into view. A second coder scored 20%–22% of each participant’s data to ensure interobserver reliability. Correlation coefficients for contact, target in view, and fixation times were >0.93. Coders agreed on 99.3% of trials for errors (k = 0.91, p < 0.001) and 94.5% of trials for whether targets were fixated (k = 0.89, p < 0.001).

4.1.5 Kinematic processing

Motion tracking data were analyzed using Matlab software. The three-dimensional coordinates of the individual markers were filtered with a zero-lag fourth-order low-pass Butterworth filter with a cut-off frequency of 6 Hz. Peak velocity was the maximum velocity of the reach trajectory. Reach duration was the time between the start of the reach and contact time; start of the reach was based on the time value that first exceeded the threshold of 5% of peak reach velocity in the vertical axis—because velocities in the horizontal and frontal planes were produced by the chair turning. Trials with reach durations <300 ms arose from extraneous velocity peak detections, and thus, were excluded. Speed was calculated by dividing the path length of the reach (sum of the trajectory of the wrist sensor) by the reach duration. Percent of deceleration time was expressed as a percentage of reach duration, calculated as the time between when peak velocity occurred and contact time.

4.2 Results

We analyzed M = 46.2 trials with targets per adult for 600 trials in total across the dataset. An additional 74 trials were excluded due to equipment failure or noise in motion-tracking data (as described above). Preliminary analyses showed no change across the session.

4.2.1 Mid-turn reaches and errors

Adults contacted the target mid-turn on 81.7% of all trials, with an average of M = 38 trials, SD = 13.1 (see triangles in Figure 3a). Of the total trials, 77.3% were error-free mid-turn reaches, M = 36 trials, SD = 12.7 (see triangles in Figure 3b).

4.2.2 Scaling of manual actions

We used GEEs to examine the proportion of total trials with leading hand use. Participants scaled hand selection during mid-turn reaches to target location and turn direction (target location × turn direction interaction), Wald χ² = 589.60, p < 0.001. Like Experiment 1, hand selection was tailored to target location relative to turn direction (see Figure 4b). When turning clockwise, adults used their leading, right hand when targets were located on the right side of space on 100% of trials. But when targets were on the left side of space, adults used their right hand on 56.4% of trials when targets were at −30 cm, p < 0.001, and right hand use gradually decreased for targets farther to the left, ps < 0.001. When turning counterclockwise, adults used their leading, left hand when the target was located on the left side of space on 89.7% of trials. On M = 66.3% of trials, adults used their left hand for board center targets and gradually decreased use of their left hand for targets located on the right side of space, p < 0.001.
For post-turn reaches, the GEE also showed an interaction effect, Wald $\chi^2 = 1831.94$, $p < 0.001$, unlike infants who only showed an effect of target location. When turning clockwise, adults always used their right hand for targets on the right side of space, and left hand for targets on the left side. When turning counterclockwise, they always used their right hand for targets on the right side of space and more than 50% of the time they used their left hand for targets on the left side (that is, they sometimes crossed their right hand over their left). Perhaps, this interaction effect emerges because most post-turn reaches (64%) occurred on the opposite side of the turning body (right side of space when turning clockwise; left side of space when turning counterclockwise), $\chi^2(5) = 15.52$, $p = 0.008$. In contrast, mid-turn reaches were equally frequent at all target locations in both turn directions, $\chi^2(6) = 1.81$, $p = 0.94$. Indeed, for post-turn reaches, targets were farther away from participants’ turning bodies, and required longer reach times as participants leaned to grasp the targets.

### 4.2.3 Timing of visual and manual object retrieval

Across adult participants, the relative timing of visual actions and reach initiation was consistent between mid-turn and post-turn reaches (Figure 6). Table 3 compares the relative timing of each visual and manual action to when the chair was at board center, and across mid- and post-turn reaches.

During mid-turn reaches, the target came into view on 100% of trials, $M = 1.47$ s ($SD = 0.10$) before the chair arrived at board center. Adults began to reach nearly simultaneously with the target appearing in view. On $M = 46.3%$ of trials, adults initiated the reach before the target came into view. Adults fixated the target on $M = 79.6%$ of trials and significantly after the target came into view. Finally, adults contacted the target significantly after fixation time. Adults rarely fixated the target after contacting it ($M = 0.3%$ of trials). We found no differences in the relative timing of visual and manual actions between error-free and non-error-free mid-turn reaches.

For post-turn reaches, the target came into view later compared to mid-turn reaches, thereby delaying the sequence of actions underlying prehension (Table 3). The relative timing of reach initiation and fixation were similar across post- and mid-turn reaches (see Figure 6b). However, contact time was significantly delayed for post-turn reaches, because post-turn reaches occurred most often when targets were on the far side of space.

#### 4.2.4 Reach kinematics

Kinematic parameters inform how proficiently adults executed reaches in the pivot paradigm. Table 4 shows the mean values of the four variables we examined for mid- and post-turn reaches. Paired t tests showed no differences in reach performance between mid- and post-turn reaches.

#### 4.3 Discussion

What does proficient prehension while pivoting look like? Adults showed a consistent sequence of visual actions relative to manual actions (target appears in view, reach starts, target fixated, target contacted). Moreover, the relative timing of visual actions and reach initiation was conserved across mid- and post-turn reaches. Reaches were fast (under 1 s) and efficient (symmetrical, bell-shaped velocity profile) in both mid- and post-turn reaches. What instigated mid-turn reaches and distinguished them from post-turn reaches was quick visual localization of the target setting off the cascade of visual–manual actions for prehension while pivoting.

## 5 General Discussion

In three experiments, we used a novel pivot paradigm—participants were passively rotated 180° toward a target object—to examine how perception and action are coordinated in real time across development. Infants and adults were free to retrieve the target mid-turn or after the chair arrived at board center, and they could reach with either hand. Both infants and adults retrieved targets mid-turn, showcasing the speed of planning and flexibility of prehension. Because target location and turn direction varied across trials, participants had to turn their head and eyes to locate the targets as the chair began to spin. Indeed, the key to mid-turn reaching was bringing the target into view earlier in the turn and initiating the reach soon after. This tight coupling between visual and manual actions was similar in infants and adults for mid-turn reaches. What changed over development was the speed of the visual and manual actions.
Prehension while pivoting: studying the whole cascade

Previous work indicates that the components required for mid-turn object retrieval are well in place by 6–8 months of age. For example, infants in the same age range also can turn head and eyes to track a target, reach for stationary and moving objects, shape their hand to grasp objects, and sit independently (Saavedra, van Donkelaar, & Woollacott, 2012; von Hofsten & Rosander, 1996; von Hofsten, Vishton, Spelke, Feng, & Rosander, 1998; Witherington, 2005). While sitting, 6- to 8-month-olds maintain balance so flexibly they can adapt their posture to changes in the ground surface (Kokkoni, Haworth, Harbourne, Stergiou, & Kyvelidou, 2018; Rachwani, Soska, & Adolph, 2017), and they can turn their torso to reach for objects in any direction (Bate & Thelen, 2004). They can reach with either hand to targets at varied locations (Jacquet et al., 2012). In addition, they can coordinate looking with a variety of manual actions such as bimanual object exploration, and do so across a variety of postures (Soska & Adolph, 2014; Soska, Adolph, & Johnson, 2010).

However, previous work did not challenge infants to coordinate all the components into a single cascade in a single task—as we did with the pivot paradigm. Here, infants had to time postural, visual, and manual actions to retrieve the target mid-turn. In the current experiments, every infant, from 6 to 15 months of age, demonstrated mid-turn reaching, and most did so at least once without reach or grasp errors. Experiment 1 showed that mid-turn reaching increased with age, as did error-free target retrieval. Experiment 2 showed that sophisticated perceptual–motor coordination characterizes successful mid-turn reaching.

5.2 Strategies for successful prehension

We instructed adults to retrieve targets as quickly as possible. But we could not do the same for infants. Nonetheless, infants discovered the adult-like strategy for successful retrieval while pivoting, as revealed in Experiment 3: As soon as the chair began turning, adults quickly turned head and eyes to bring the target into view and simultaneously brought up the leading hand; then, using visual information from the periphery, they guided the leading hand to the target, and shaped the hand for retrieval.
Although most frequent for adults’ mid-turn, error-free retrievals, the adult-like strategy was not obligatory for successful mid-turn reaching in either infants or adults. For example, fixing the target before hand contact is optional, not required. Successful reaches can start simultaneously with the target appearing in view or long after the target was in central view. Depending on the target’s location, the trailing hand may grasp it mid-turn. Moreover, even on trials where they eventually contacted and retrieved the target, both infants and adults also exhibited reach and grasp errors—striking the board or misshaping the grasping hand.

Put another way, although the adult-like strategy dominates adults’ perceptual–motor repertoires in the pivot paradigm, this strategy exists in infants as young as 6 months of age. For prehension while pivoting, different ways of coordinating perception and action can co-exist in infants’ repertoires. What changed with development was the ratio of adult-like retrieval strategies relative to unsuccessful prehension behavior. As Bernstein (1996) proposed, variability in performance is endemic to any new or developing skill, but eventually successful strategies that were initially rare begin to dominate the motor repertoire and displace noisy, unskilled behavior.

### 5.3 Mechanisms of developmental change

How might infants converge on the adult-like strategy? What factors lead to age-related increase in the frequency and accuracy of mid-turn reaching? The speed of visual and manual actions is the critical factor. Previous work showed age-related increases in reaching speed (Berthier & Keen, 2006; Thelen, Corbetta, & Spencer, 1996; von Hofsten, 1979), visual search strategies (Bertenthal & von Hofsten, 1998) and head-hand coupling (Savelsbergh, von Hofsten, & Jonsson, 1997). Likely, faster planning of visual and manual actions provides infants with more time to respond adaptively and accurately, similar to infants catching moving targets (von Hofsten, 1983). Moreover, all of these factors also play a critical role in prehension during active rotation—yet whether their roles are qualitatively different or simply amped up in difficulty require further research. Presumably, with more everyday experience executing reaches in a variety of contexts and locations, infant prehension becomes faster, and coordination between perceptual and motor systems becomes more efficient and consistent (Smith & Thelen, 1993; Thelen et al., 1993; von Hofsten, 1991).

Fast and efficient visual and manual actions are rooted in improvements in postural control (Bertenthal & von Hofsten, 1998; Rachwani et al., 2013; Rachwani, Santamaria, Saavedra, & Woollacott, 2015; Reed, 1989). Postural control sets up the prerequisites for looking around, orienting eyes, head, and trunk to the target location. Indeed, participants had to actively turn torso, head, and eyes to locate targets before the chair passively brought the target into view. Additionally, postural control counteracts the forces imposed by passively rotating the chair and actively lifting the arm to reach (Bortolami et al., 2008; Pigeon, Bortolami, DiZio, & Lackner, 2003a, 2003b). Ongoing research affirms the critical role of posture in prehension while pivoting (Rachwani, Golenia, Herzberg, & Adolph, 2019).

Although not measured in the current studies, hand dominance may also affect planning prehension while pivoting. As hand preferences stabilize in infancy (Michel, 1998; Nelson et al., 2013), reaches with the right hand and on the right side of visual space become more efficient than reaches with the left hand and on the left side of space (Fagard et al., 2009; Morange & Bloch, 1996; Morange-Majoux & Dellalotas, 2010; Netelenbos & Gonzalez, 2015). An emerging right-hand advantage might have led infants and adults to execute mid-turn reaches more frequently with the right hand when the right hand led the turn. Indeed, on clockwise turns, although the right hand would have to cross the body’s midline to contact targets on the left after the chair reached board center, infants and adults happily and often used the right hand. But the opposite—crossing over midline with the left hand on counterclockwise turns—was more rare.

Finally, motivation likely plays a role in retrieving objects while pivoting. In principle, although infants could have the requisite perceptual–motor coordination, there is no intrinsic reason for them to reach mid-turn or actually retrieve the object and return it to the assistant. However, in practice, we found that after a few warm-up trials, infants were highly motivated to retrieve the targets as quickly as they could—without explicit instructions. As in previous work, they appeared to delight in the “game” of spinning back and forth and retrieving fun small toys to hand to the assistant. Similar to studies with infants crawling or walking down steep slopes or over narrow bridges and large gaps, experimenters have to motivate infants to display their best performance in novel lab tasks (Adolph, Rachwani, & Hoch, 2018).

### 5.4 Conclusions

Pushing the boundaries of infants’ visual–manual systems revealed a coordinated cascade of actions—visual, manual, and postural—that expands previous conceptions of the development of prehension skills. Infants searched for the target on each trial, quickly planned which hand to use based on turn direction and target location, adjusted their reach trajectory and controlled their upper body to account for rotational movement, continually updated their visual frame of reference with respect to their bodies, and guided their reaching and grasping movements to retrieve the target. Studying the entire cascade of visual–manual actions, rather than piecemeal components, revealed sophisticated perceptual–motor coordination in infants and adults. Considering perception and action as a whole provides a novel paradigm for characterizing development of prehension skills.

### ACKNOWLEDGMENT

This research was supported by National Institute of Health and Human Development Grant R37-HD33486 and R01-HD33486 to...
Karen E. Adolph. Portions of this work were presented at the 2009 International Conference on Perception and Action, Minneapolis, MN and the 2010 International Conference on Infant Studies, Baltimore, MD. We gratefully acknowledge the infants and parents who participated. We thank the members of the NYU Infant Action Lab for assistance collecting and coding data and preparing figures.

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