CHILD DEVELOPMENT

Child Development, September/October 2019, Volume 90, Number 5, Pages 1559–1568

Postural, Visual, and Manual Coordination in the Development of Prehension

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We investigated the real-time cascade of postural, visual, and manual actions for object prehension in 38 6- to 12-month-old infants (all independent sitters) and eight adults. Participants' task was to retrieve a target as they spun past it at different speeds on a motorized chair. A head-mounted eye tracker recorded visual actions and video captured postural and manual actions. Prehension played out in a coordinated sequence of postural–visual–manual behaviors starting with turning the head and trunk to bring the toy into view, which in turn instigated the start of the reach. Visually fixating the toy to locate its position guided the hand for toy contact and retrieval. Prehension performance decreased at faster speeds, but quick planning and implementation of actions predicted better performance.

Object prehension—the ability to contact, grasp, and retrieve an object—is not merely manual. Sure, prehension involves manual actions of reaching and grasping. But in addition, visual information must guide the hand to the object and shape the hand to grasp and retrieve it. Head and trunk movements are required to visually locate the object and prepare the body for destabilizing forces from arm movements. Thus, prehension requires precise temporal-spatial coordination among multiple systems occurring within milliseconds.

Despite wide-spread recognition that object prehension entails postural, visual, and manual actions, previous developmental research is fragmented. The communal research program assumes that piecemeal studies of components will lead to understanding the whole. Some studies focus only on reaching—extending the arm to contact the object (Berthier & Keen, 2006; von Hofsten, 1991; Thelen et al., 1993). Some focus only on grasping—orienting the hand and configuring grip size (Lockman, Ashmead, & Bushnell, 1984; Witherington, 2005). A smaller set of studies examine pairs of components such as visual guidance of reaching (Clifton, Muir, Ashmead, & Clarkson, 1993; Corbetta, Thurman, Wiener, Guan, & Williams, 2014; Lee & Newell, 2012) or grasping (von Hofsten & Ronnqvist, 1988), or effects of posture on reaching (Harbourne, Lobo, Karst, & Galloway, 2013; Rachwani et al., 2013; Rachwani, Santamaria, Saavedra, & Woollacott, 2015), or effects of object distance on leaning and reaching (Adolph, 2000; Yonas & Hartman, 1993). Moreover, infants typically sit on caregivers' laps or in a semireclined seat, and researchers place objects—always within infants' field of view—at midline or locations across the horizontal reaching space (Clifton et al., 1993; von Hofsten, Vishton, Spelke, Feng, & Rosander, 1998; Rat-Fischer, O'Regan, & Fagard, 2012). Consequently, we have a detailed understanding of individual components of prehension but know little about *coordination among* components in real time or across development.

Each component undergoes dramatic developmental change. Infants' first reaches are crooked, jerky, and slow (Berthier & Keen, 2006; von Hofsten, 1991; Thelen, Corbetta, & Spencer, 1996). Infants' first grasps often occur without an adequate plan for grip configuration, so they contact the object with their hand closed (von Hofsten & Lindhagen, 1979; Lee, Liu, & Newell, 2006). Initially, infants rely on proprioceptive feedback rather than vision to adjust their hand trajectory (Clifton et al., 1993). Postural control is so poor that merely lifting the arm causes infants to lose balance and interrupts object retrieval and exploration

This research was supported by National Institute of Health and Human Development Grants R37-HD033486 and R01HD033486 to Karen E. Adolph. Portions of this work were presented at the 2017 Society for Research in Child Development, Texas. 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.

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0009-3920/2019/9005-0008
DOI: 10.1111/cdev.13282

(Rachwani et al., 2013; Rachwani et al., 2015; Soska & Adolph, 2014). Over the ensuing months, reaching becomes straighter, smoother, and faster (Thelen et al., 1996). The hand opens in preparation for grasping and manipulating the object. Visual guidance becomes so adept that infants can catch moving objects (von Hofsten et al., 1998). As infants acquire more postural control, they can easily reach, grasp, and explore objects. Indeed, by the time infants become accomplished sitters, all the components for prehension are in place.

This study aimed to obtain a more holistic picture of the development of object prehension by testing the temporal-spatial coordination of postural, visual, and manual actions. Previous work used a "pivot paradigm" to study infant reaching (Ekberg et al., 2013; Soska, Rachwani, von Hofsten, & Adolph, 2019). Infants sat on parents' laps on a swivel chair and were spun by an experimenter 180° to face the board. Sometimes infants spontaneously contacted the toy before the chair completed the 180° turn, thus showing prospective control of the entire postural–visual–manual cascade.

Here, we used head-mounted eye tracking and a continuously pivoting chair to study the coordination of actions for prehension. Infants sat on a motorized chair that rotated them 360° past a toy located at varying heights at slower and faster speeds. With this novel "pivot-past paradigm," the task was to retrieve the toy before it was out of reach. On each trial, infants needed to quickly engage the postural (turn head and trunk to visually locate the toy) and visual systems (continually track toy position relative to body position), and plan manual actions accordingly. The faster speed required infants to locate the target and plan the reach earlier in the chair rotation. Easy baseline trials, where the chair rotated only 180°, were included so infants could retrieve the toy without time constraints. Given the challenges of the task, we tested infants with a range of sitting experience and a comparison sample of adults.

We tested two hypotheses. Hypothesis 1: *Infants coordinate postural, visual, and manual actions as body position changes*. We predicted a real-time cascade of actions starting with turning the head and trunk to bring the toy into view, which in turn instigates the reach. Visually fixating the toy to locate its position guides the hand for contact and retrieval of the toy. Thus, postural actions support visual and manual actions, and visual actions guide manual actions. Hypothesis 2: *Starting the sequence of actions earlier results in more successful prehension*. Given trial-to-trial variations in target location, speed of rotation, and turn direction, infants could not merely lift an arm to a fixed position after the chair began to rotate. We expected the faster speed to be more challenging for coordination of actions, and consequently impair prehension performance.

Method

Participants

We tested 38 infants (18 boys), 6–12 months of age, M = 9.04 months (Figure 1A). All were born at term (birth weights 2.4–4.6 kg, M = 3.2 kg). Most families were white, middle-class, and college educated; twenty-seven spoke English as their primary language, and eleven were bilingual. Parents reported the first day they saw their infants sit hands free with their legs outstretched on the floor for $\geq$ 30 s. Sitting experience ranged from 0 to 174 days and was correlated with age, $r(35) = .82$, $p < .001$. Parent report was unavailable for one infant. An experimenter verified that all infants could sit independently for a few seconds, well enough to participate. Data from an additional 13 infants were not analyzed due to equipment failure (n = 3), experimenter error (n = 2), refusal to sit on the chair (n = 2), inability to sit (n = 2), or failure to complete > 25% of trials (n = 4).

We also tested a comparison group of eight 18- to 23-year-old adults (five women; Figure 1A). All were right-handed and had normal vision.

Apparatus and Procedure

Infants sat, thighs strapped, on a bench attached to a motorized chair, with caregivers seated behind them (Figure 1B). Infants reached for small (< 3 cm) toys varying in vertical location (eye or chest level) affixed with magnets to a 45 × 45-cm board. Parents were instructed not to talk to infants or point to toys. Adult participants sat on the motorized chair and reached for targets at eye or chest level. The experimenter adjusted chair distance to keep targets within reach.

Similar to the setup in Ekberg et al. (2013) and Soska et al. (2019), trials began with participants facing the experimenter. An assistant placed targets high or low, according to a random number generator. Custom software spun the chair 180° (chair stopped at toy) or 360° (chair stopped at experimenter). The 180° trials were easy because time constraints and disruptions to posture were reduced. The chair spun at "slow" (35°/s) and "fast" speeds (45°/s) for infants and slow (70°/s) and fast speeds

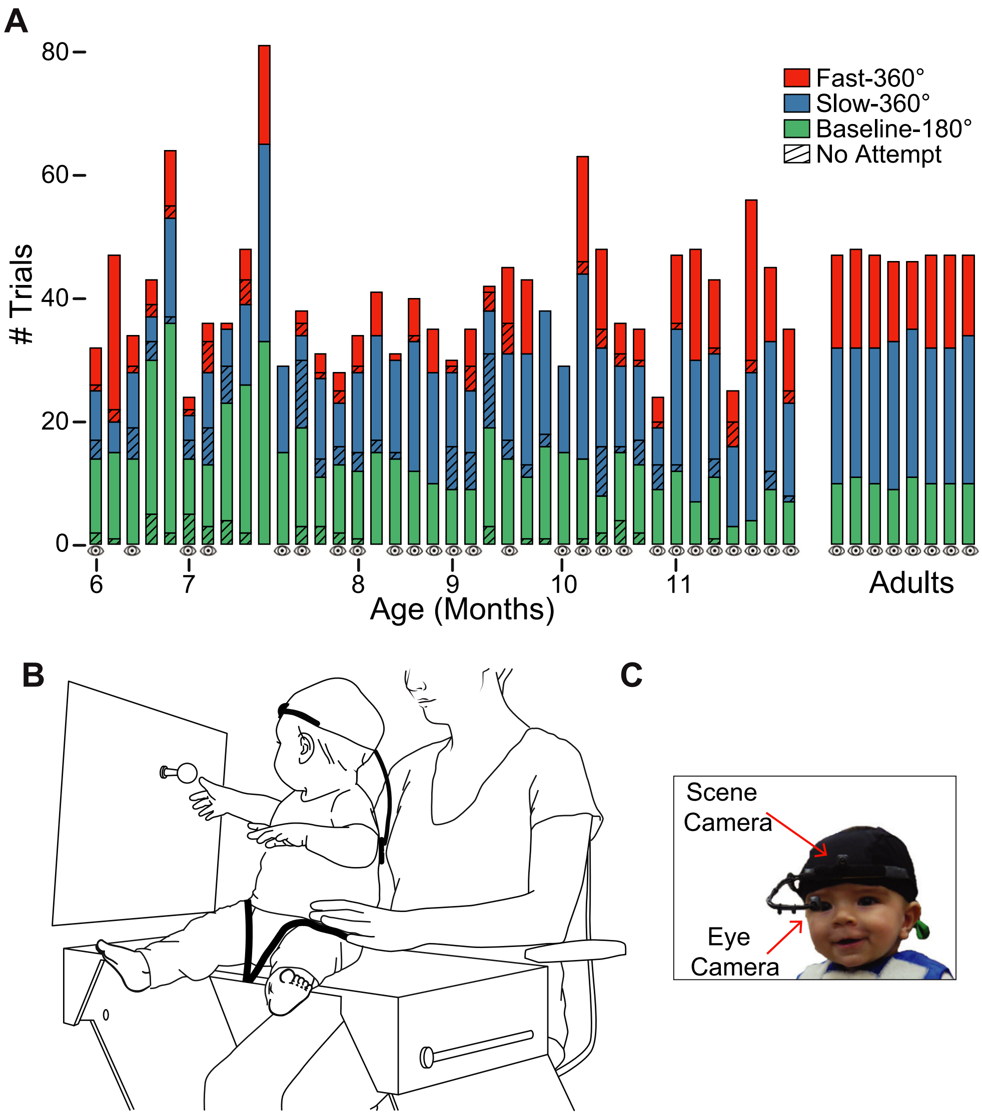

Figure 1. Trials and procedure. (A) Total number of trials for each participant across age during baseline-180° (green), slow-360° (blue), and fast-360° (red) conditions. Note each participant is shown equidistant from the next, so ages are not evenly spaced. Diagonals denote trials with no attempted reaches. Eye icon denotes participants that wore the head-mounted eye tracker. (B) Line drawing shows a typical infant sitting on the bench attached to the motorized chair with the caregiver seated behind. Infant reaches toward a target placed at one of two randomly presented vertical locations on the reaching board. (C) Photo shows infant wearing head-mounted eye tracker. Scene camera records view of the reaching board and target object. Eye camera records movements of the infant's eye. Software calculates infant's point of gaze in the scene.

(100°/s) for adults. Pilot testing showed that even faster speeds precluded retrieval by infants and made adults nauseous. The selected speeds ensured that participants were comfortable and infants could contact the toy on some trials. Turn direction alternated between trials.

Testing began with several baseline-180° trials to teach infants the game of retrieving toys. Then, the experimenter presented two slow-360° trials, followed by one fast-360° trial. After that, slow- and fast-360° trials were randomly ordered. If infants fussed or did not retrieve the toy on three consecutive 360° trials, the experimenter presented a baseline-180° trial to renew their motivation, and then presented two slow- and one fast-360° trial before returning to random orders. If infants retrieved the toy, the experimenter removed it from their hands before the next trial. Infants received 24–81 trials (M = 40.0) and adults received 46–48 trials (Figure 1A). Sessions lasted ~50 min for infants and ~30 min for adults.

We video recorded participants' actions from an overhead view and two side camera views. The three views were mixed onto a single video frame. The full data set and an excerpt of an infant performing the task are shared on Databrary (https://nyu.databrary.org/volume/735).

Head-Mounted Eye Tracker

Participants wore a Positive Science (https://www.positivescience.com) head-mounted eye tracker (Figure 1C): A wide-angle *scene camera* above the right eyebrow recorded the scene (101.6° × 73.6°), and an *eye camera* recorded movements of the right eye. Infant and adult headgear and the calibration process were identical to Franchak, Kretch, and Adolph (2018).

As noted by the "eye" icon in Figure 1A, we collected eye-tracking data from all eight adults and 25/38 infants, (14 boys), 6–12 months of age, $M = 9.35$ months ($SD = 1.63$). We did not put the tracker on the first 10 infants, and three subsequent infants removed the tracker but happily reached.

Data Coding

A primary coder used Datavyu (www.datavyu.org) to identify onsets of critical events. For each trial, the coder scored whether participants *attempted to reach* or the toy flashed by before the reach began. For attempted reaches, the coder identified when the *head-trunk turn* started; the *toy appeared in the field of view*; the *reach started* (continuous movement of arm toward toy); *fixation* of the toy (gaze cursor on toy for ≥ 3 frames); *toy contact*; and *toy retrieval* (when toy lifted from board). Based on average spin velocity and onset–offset of chair movement, we calculated degree of chair rotation for each event. Last, coders scored *contact errors* (touched board prior to toy contact) and *retrieval errors* (readjusted hand position or changed hands after toy contact).

A "reliability" coder scored 25% of each session. Coders agreed on ≥ 96.3% of trials for whether participants turned their head, fixated the toy, and errors ($\kappa s \geq .77$, $ps < .001$); correlation coefficients for head latency (chair onset to head turn), fixation duration (toy in view to fixation), reach duration (reach initiation to contact), and retrieval duration (contact to retrieval) were $rs \geq .96$, $ps < .001$.

Results

Infants attempted to reach on 91.9% of baseline-180° trials, 81.1% of slow-360° trials, and 78.4% of fast-360° trials. They contributed $M = 13.1$ baseline-180° trials, $M = 14.1$ slow-360° trials, and $M = 7.9$ fast-360° trials (Figure 1A). Three infants did not receive fast-360° trials because of software problems. Older, more experienced sitters had fewer baseline trials, $rs \geq -.54$, $ps \leq .001$ and more 360° trials, $rs \geq .43$, $ps \leq .007$. Preliminary analyses showed no effects of sex, toy location, or turn direction, $ts \leq 1.51$, $ps \geq .14$, so these variables were collapsed for analyses.

Adults attempted to reach on every trial (Figure 1A). They contributed $M = 10.1$ baseline-180° trials, $M = 22.6$ slow-360° trials, and $M = 14.1$ fast-360° trials.

See Appendix S1 for information on hand selection.

Prehension Performance

Infants displayed five ordered categories of *prehension performance*, depending on whether the trial included: (a) arm lift only; (b) arm lift and toy contact with errors; (c) arm lift and error-free contact only; (d) arm lift, contact, and retrieval with errors; and (e) arm lift, error-free contact, and retrieval (Figure 2 legend).

Figure 2A shows the proportion of trials infants displayed each level of performance in each condition. The difference in hues shows that on baseline-180° trials, most attempts ended with retrieval, $M = 80.1\%$; on slow-360° trials most attempts ended in contact-only ($M = 50.3\%$); and on fast-360° trials, most attempts ended with arm lifts, $M = 49.8\%$. Adults, in contrast, retrieved the toy on 99.7% of trials across conditions.

The scatter plots in Figure 2B show infants' average prehension performance for each condition by sitting experience and age. The darker bars in Figure 2A and the fit lines in Figure 2B show that older, more experienced sitters displayed better performance, $rs \geq .49$, $ps \leq .002$. Controlling for age, the partial correlation between sitting experience and performance was significant for the slow-360° condition, $r(31) = .35$, $p = .038$, but the converse (controlling for sitting experience) did not hold for age.

Spatiotemporal Sequence of Actions

The colored rings in Figures 3A and 3F show the range across participants for the average degree of chair rotation for each postural, visual, and manual action (black lines denote group means). During each trial, participants could engage in some or all

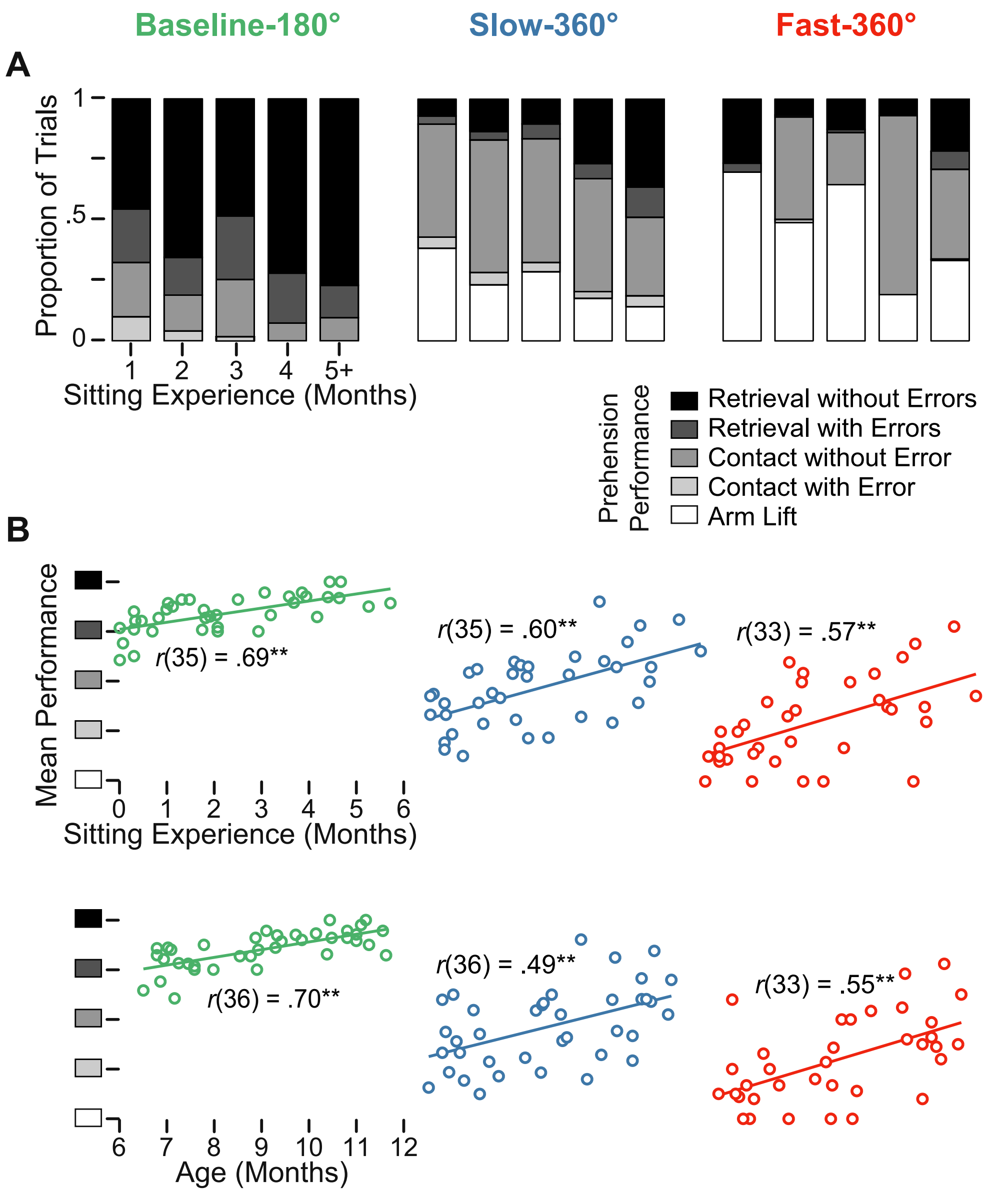

Figure 2. Prehension performance. All data are plotted on the same axes as shown in the left graphs. (A) Proportion of trials infants displayed each level of prehension performance (following the legend in the inset) in each speed condition, binned by infant's sitting experience. Legend shows five ordered categories (gray hues) of prehension performance observed in the task. (B) Scatter plots show each infant's average prehension performance (average out of the five-level scale displayed in the legend) for each of the three conditions by infant's sitting experience (top panel) and age (bottom panel).

of the actions we coded. Chair rotation began at 0°; was midway through its rotation at 90°; parallel to the toy at 180°; and actions could occur beyond 180° in the 360° conditions. Actions that occurred before 180° reflect proactive reach planning. We found no differences for timing of postural and manual actions between infants who wore the eye tracker and infants who did not, *ts* ≤ 1.74, *ps* ≥ .10, thus timing of postural and manual actions was analyzed for all infants.

Postural and visual actions were omnipresent during every attempt: Turning head and trunk occurred on *Ms* = 93.6%–98.1% of trials across conditions, the toy appeared in view on 100% of trials, and fixations to the toy occurred on *Ms* = 77.6%–89.0% of trials. Thus, on *Ms* = 77.9%–82.6% of trials across conditions, infants incorporated all postural and visual actions in the attempt.

Moreover, when infants incorporated postural–visual–manual actions in the attempt, actions

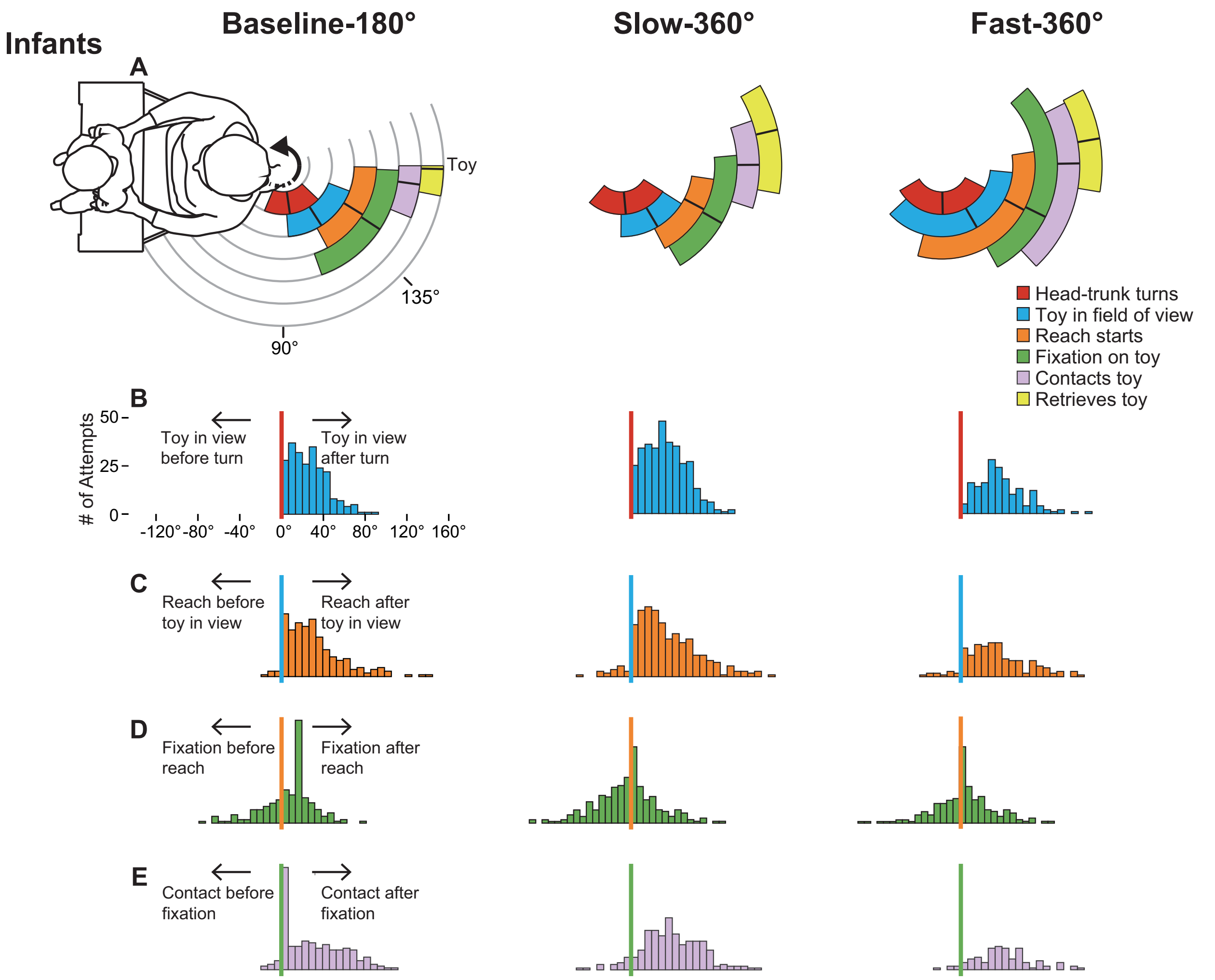

Figure 3. Spatiotemporal sequence of postural, visual, and manual actions. All data are plotted on the same axes as shown in the left graphs. Rings in (A and F) show average degree of chair rotation when each action occurred for infants and adults. Length of rings denotes the range across participants and black lines represent the means. Chair rotation began at 0°. was midway through its rotation at 90°, and was parallel to the toy at 180°. Actions could occur beyond 180° in the 360° conditions. Frequency histograms in (B–E) and (G–J) show relative timings of actions for infants and adults, measured in degrees for comparisons across participants and different speed conditions. Histograms in (B and G) show when the toy appeared in the field of view relative to head-trunk turn (vertical red line); (C and H) show when the reach started relative to the toy appearing in the field of view (vertical blue line); (D and I) show first fixation to toy relative to when the reach started (vertical orange line); (E and J) show toy contact relative to fixation of the toy (vertical green line).

occurred in a temporal sequence (see frequency histograms in Figures 3B–3E). Prehension started with turning head and trunk to visually search for the toy. It occurred before the toy came into view on 100% of trials, before the reach started on *Ms* = 97.6%–99.5% of trials, and always before fixation to the toy, toy contact, and retrieval. The toy came into view prior to starting the reach on *Ms* = 92.3%–97.2% of trials across conditions and always occurred prior to contact and retrieval. Fixations occurred before or after reach initiation (*Ms* = 47.6%–54.9% of trials) but occurred before contact on *Ms* = 87.3%–97.7% of trials. Infants continued to maintain fixation to the toy or made 1–2 refixations, *Ms* = 1.5–1.8 fixations across conditions. The total fixation duration was *Ms* = 0.84–1.5 s. Contact occurred as infants were passing the toy and thus came later in the trial. Soon after contact, retrieval occurred.

Thus, the average percentage of trials across conditions in which infants' head-trunk turn preceded visually locating the toy, visually locating the toy preceded reach initiation, and fixation preceded toy contact, were all significantly > 50% (greater than chance level), one-sample $ts \geq 11.19$, $ps < .001$. Of the times infants incorporated all postural and visual

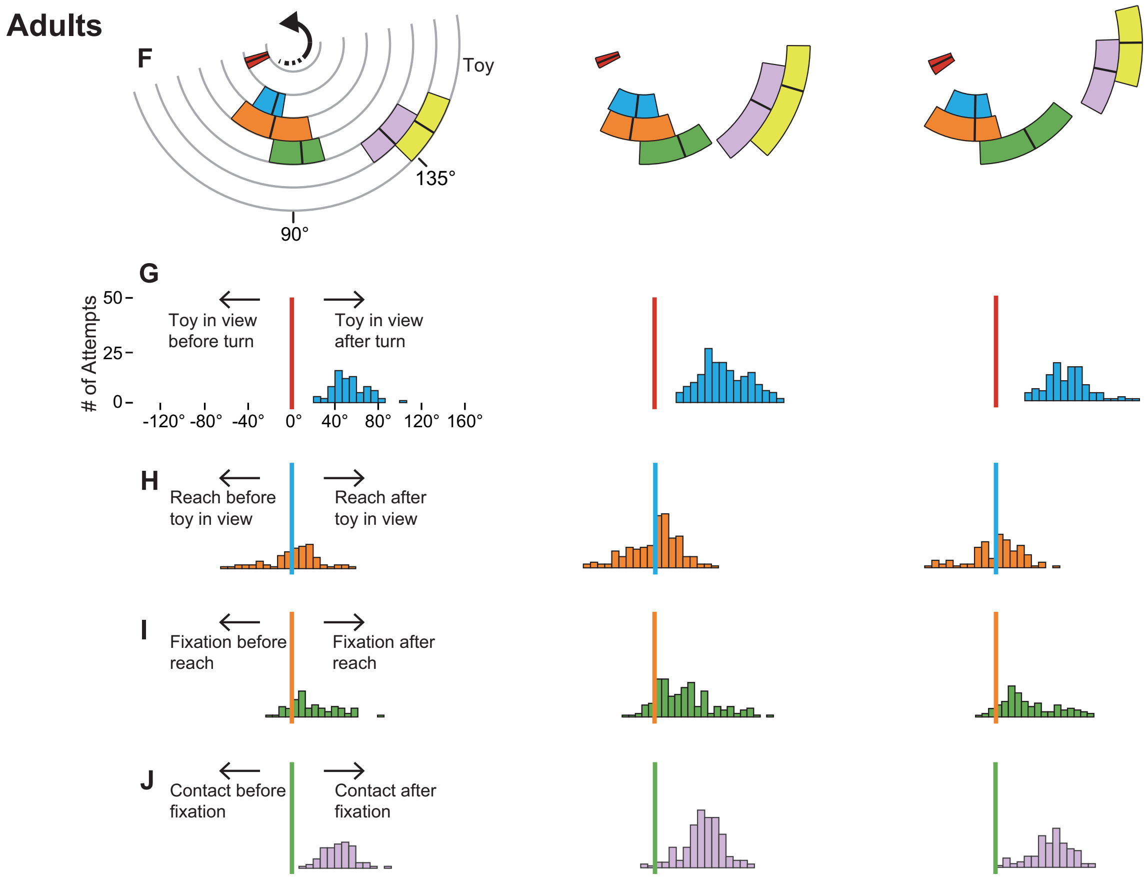

Figure 3. (*Continued*)

actions for contacting the toy, infants displayed the canonical sequence (first turning head and trunk, then visually locating the toy, then lifting an arm and fixating the toy prior to contact) on Ms = 85.0%–97.2% of trials across conditions, Ms significantly > 50%, one-sample $ts \geq 7.56$, $ps < .001$. The prevalence of the temporal sequence between pairs of actions and the entire canonical sequence did not vary across infants' age, sitting experience ($rs \leq .35$, $ps \geq .083$), or condition, $Fs \leq 2.98$, $ps \geq .061$.

Adults always incorporated postural–visual–manual actions in their attempts and performed each action earlier in the turn compared to infants, $ts \geq 24.28$, $ps \leq .001$ (see Figure 3F). Like infants, the sequence was consistent. Head-trunk turning always started before the target came into view. The reach started before or after the target came into view (Ms = 59.2%–68.5% of trials across conditions). Fixations occurred after reach initiation (Ms = 82.5%–92.5% of trials) but before contact (Ms = 98.1%–100% of trials). All Ms significantly > 50%, one-sample $ts \geq 5.65$, $ps \leq .001$, except for the average percentage of trials in which adults' started reaching after the target came into view (see Figures 3G–3J). Compared to infants, adults made fewer fixations per trial (Ms = 1.01–1.03 fixations across conditions), and their total fixation duration was shorter (Ms = 0.56–0.77 s), $ts \geq 4.28$, $ps \leq .001$.

To formally test effects of speed and timing of actions (chair rotation degree when actions began) on infants' prehension performance, we used generalized estimating equations because each infant's attempted trials were correlated and not distributed evenly across conditions. We used an exchangeable covariance structure with number of attempted trials as a scale weight factor. We used Sidak corrections for multiple comparisons. We included speed condition as a fixed-effect factor and timing of head-trunk turn, toy in view, reach initiation, and fixation of toy as covariates. We also included sitting experience as a covariate to examine effects of condition and timing of actions while statistically controlling for experience. Data were normalized to the mean of each covariate.

Results showed a main effect of condition on prehension performance, Wald $\chi^2s \geq 88.01$, $ps < .001$.

Infants' performance was better (closer to 5, see Figure 2) for baseline-180° compared to the 360° conditions. And performance was better during the slow-360° condition compared to the fast-360° condition, all $ps \leq .001$. Earlier onsets of actions predicted better prehension performance during the 360° conditions, Wald χ^2s ≥ 47.50, $ps < .001$. Decomposing the action onset × condition interaction, earlier onsets predicted better performance in the fast-360° condition compared to baseline-180° (βs $\geq -.02$, $ps < .001$) and in the slow-360° condition compared to baseline-180° (βs $\geq -.01$, $ps < .001$). Moreover, with more months of sitting experience, prehension performance improved overall, Wald χ^2s ≥ 24.58, $ps < .001$.

Across trials, infants' prehension performance and timing of actions improved. See Appendix S2.

Discussion

Using head-mounted eye tracking in a novel "pivot-past" paradigm, we showed that infants coordinate postural, visual, and manual actions for prehension during whole-body rotation by 6 months of age, and prehension continuous to improve thereafter. Prehension performance decreased at faster, more challenging speeds. Infants and adults shared a common spatiotemporal sequence of postural–visual–manual coordination. The key difference was in the *speed* of actions. Faster implementation of the sequence predicted better prehension performance.

Real-Time Cascade of Postural, Visual, and Manual Actions

Every infant showed evidence of prospective control across time and space and across postural, visual, and manual systems. Infants turned head and trunk to locate the toy in their field of view, and lifted an arm toward the toy before their bodies were in front of it. This finding demonstrates, for the first time, prospective control and temporal-spatial coordination of postural, visual, and manual actions in young infants. In previous work where toys were presented in infants' field of view and recording eye gaze was limited to what infants saw on a screen, infants' ability to coordinate multiple systems was masked (e.g., Corbetta et al., 2014; Lee & Newell, 2012; Rat-Fischer et al., 2012; von Hofsten, 1991). Without the time constraints imposed by pivoting infants past the toy and the use of head-mounted eye tracking, this finding would not have been possible. Moreover, prospective control was strongly related to more advanced prehension performance, similar to previous work showing that infants gear hand actions to catch fast-moving toys (van der Meer, van der Weel, & Lee, 1994). For adults, every postural, visual, and manual action occurred earlier in the turn compared to infants. Early reaching in adults was not because adults have longer arms given that the results hold even after normalizing data to arm length.

A second critical finding was that object prehension played out in an organized spatiotemporal sequence—a *real-time perception-action cascade*. Infants first turned their head and trunk, then visually searched for the toy prior to lifting an arm, and fixated the toy prior to contacting it. Of course, certain actions logically followed other actions (fixations followed visually locating the toy and toy contact followed reach initiation). However, other actions could occur in various orders. Visually locating the toy could follow head-trunk turning or it could occur without a turn (by waiting for the toy to appear in view as the chair rotated past). Reach initiation could occur before or after visually locating or fixating the toy. Fixations could occur before or after contacting the toy. The sequence was spatially and temporally geared toward the toy because every action was logically ordered depending on participants' proximity to the toy and on their prior movements. Turning head and trunk to locate the toy in the field of view instigated lifting the arm. Infants rarely reached without visually locating the toy. In fact, in the few instances when the chair spun and there was no toy on the board because of experimental error, infants turned their body and the board appeared in the field of view, but infants did not begin to reach. However, fixating the toy before starting the reach was optional—similar to infants' locomotor exploration where fixations to a destination can occur while stationary or in the midst of a bout (Hoch, Rachwani, & Adolph, 2019). Fixating the toy guided fine tuning of the arm trajectory and hand shape for grasping the object. Thus, earlier behaviors generate information for later behaviors (Kretch & Adolph, 2017).

Moreover, failure to perform earlier actions impeded later actions. The real-time cascade broke down when the chair spun at faster speeds. Under less challenging constraints on slow-360° trials, infants showed better performance. Without any time constraints on easy baseline-180° trials, every infant easily retrieved the toy. So although prospective control during object prehension may seem simple, it is not! Actions must be selected, timed, and shaped prospectively to adapt to the changing environment (Gibson, 1979). A slight delay in infants' implementation of the postural–visual–motor cascade during the fast-360° condition typically resulted in regression to the prereaching performance of a 2-month-old (von Hofsten, 1984), where all infants could manage to do was to lift their arm as they whizzed past.

Coordination of Postural, Visual, and Manual Actions Across Development

Visual interest for toys begins early: Neonates fixate objects in view (von Hofsten, 1982). By 3–4 months, infants can contact objects if their posture is supported (Rachwani et al., 2015), and by 5 months, infants can grasp objects (von Hofsten & Ronnqvist, 1988). By 6 months, infants can sit independently and orient eyes–head–trunk while stationary to reach for objects (von Hofsten et al., 1998; Rochat & Goubet, 1995).

This study shows that infants can coordinate all these actions on the fly. Every infant, including the most novice sitter, orchestrated turning, looking, and arm movements for prehension. But no presitter could do the task. Thus, learning to sit sets up the necessary conditions for looking around and handling objects while stationary and moving—the common situations in everyday life. Sitting instigates a cascade of visual and manual developments, and instigates new ways of accessing or "prehending" the world visually and manually. As such, the utility of previously developed skills—here visual and manual actions—must await the development of sufficient sitting control to play out in synchrony. Posture is the bottleneck.

Children and adults become so adept at coordinating multiple systems that they can reach while walking and catch a frisbee while running. Likely, speed of actions is a critical factor for mature coordination, as in infants' catching skills (von Hofsten et al., 1998). Faster planning of postural–visual–manual actions enables more time to respond adaptively and accurately. Presumably, with more everyday experience executing reaches in a variety of contexts, locations, and postures, coordination among postural–visual–manual actions becomes more efficient, and subsequently prehension becomes more accurate.

Conclusions

Outside the laboratory, toys and other interesting targets are rarely located at infants' shoulder height within their visual field. In everyday life, infants must find the toy and then retrieve it. Doing so requires a real-time cascade of postural–visual–manual actions, each executed rapidly in sequence. Successful planning and implementation of the real-time cascade awaits independent sitting control and improves thereafter. By recording eye gaze in infants in the pivot-past paradigm, we documented for the first time the coordination among postural–visual–manual systems for prehension.

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Supporting Information

Additional supporting information may be found in the online version of this article at the publisher's website:

Appendix S1. Hand Selection

Appendix S2. Changes Across Trials