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Visual-motor coordination in natural reaching of young children and adults

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Abstract

The current study investigated eye-hand coordination in natural reaching. We asked whether the speed of reaching related to the quality of visual information obtained by young children and adults. Participants played with objects on a table while their eye and hand movements were recorded. We developed new techniques to find reaching events in natural activity and to determine how closely participants aligned gaze to objects while reaching. Reaching speed and eye alignment were related for adults but not for children. These results suggest that adults but not children adapt reaching movements according to the quality of visual information (or vice-versa) during natural activity. We discuss possibilities for why this coordination was not observed in children.

Keywords: reaching; visual guidance; eye tracking; natural vision; motor development

Introduction

Infants' learning is rooted in more than passive observation of objects in the world. Infants actively engage with objects, and, as such, object engagement depends on infants' developing action systems. Indeed, motor development and cognitive development are closely linked in development (Iverson, 2010; Ruff & Rothbart, 1996). For example, learning to reach allows infants to acquire objects and explore them manually, and visual-manual exploration facilitates learning about object properties (Soska, Adolph, & Johnson, 2010). However, reaching depends on learning how to acquire visual information for guiding action—selecting where to look to support the task at hand from many potential gaze targets in the environment.

Visual information is critical for planning and guiding manual actions. In laboratory experiments with adults, reducing or removing access to visual information reliably degrades performance (Ma-Wyatt & McKee, 2006; Schlicht & Schrater, 2007; Sivak & MacKenzie, 1990). But in real life, visual information is not manipulated; it is actively selected. Observers choose where to direct gaze from moment to moment from a variety of targets that compete for attention. Eye movements may be recruited to gather information relevant to guiding action, but may also be used to observe events or interact with social partners. How do observers coordinate gaze when controlling manual actions in a real world task? In addition, how does visual guidance of natural reaching differ between actors of different skill levels—novices (young children) and experts (adults)?

Visually-guided reaching in adults

In laboratory tasks, aligning the eye to the target of a reach results in better reaching execution. Spatial acuity in the periphery is worse than in central vision, thus, viewing targets in the periphery leads to poor localization of the target (Levi & Klein, 1996) and the hand relative to the target (Saunders & Knill, 2004). Lacking accurate information for guiding the reach, actors compensate by adapting the kinematics of transport and prehension. When eye alignment is experimentally manipulated by viewing targets in the periphery at varying eccentricities, adults' maximum grip aperture increases to compensate for uncertainty in target size and location when grasping (Schlicht & Schrater, 2007). Similarly, endpoint accuracy becomes more variable when rapidly pointing to targets viewed in the periphery compared to targets in central vision (Ma-Wyatt & McKee, 2006). Forcing participants to view targets peripherally by wearing a contact lens that blocks central vision reduces reaching velocity and disrupts prehension (Sivak & MacKenzie, 1990). Moreover, the effects of peripheral viewing on reaching are not "all or nothing": Parametric manipulations of eye alignment reveal a linear relation between target eccentricity and maximum grip aperture (Schlicht & Schrater, 2007).

Because viewing targets in central vision facilitates reaching performance, it would be reasonable to expect that actors would choose to align gaze to reaching targets during natural manual activity. Indeed, participants fixate objects before reaching to them in head-mounted eye tracking studies of natural tasks such as making a cup of tea (Land, Mennie, & Rusted, 1999) and preparing a sandwich (Hayhoe, Shrivastava, Mruczek, & Pelz, 2003). In these tasks, observers are free to look wherever they want, unlike in experimental tasks that manipulate participants' vision of targets. Although participants reliably look to objects before reaching, object fixations are not stereotyped. The timing of object fixations varies considerably and gaze often leaves the target object before the hand arrives (Hayhoe et al., 2003; Land et al., 1999; Pelz, Hayhoe, & Loeber, 2001). Moreover, object fixations are not obligatory. Hayhoe and colleagues (2003) found that 13% of reaches were not accompanied by object fixations. In these cases, actors might have relied on peripheral vision to guide the hand. But was reaching performance hindered when gaze was not aligned to the target? Because reaching kinematics were not measured, it is unknown whether aligning the eyes to the target related to reaching performance.

Development of visually-guided reaching

The role of vision in guiding reaching changes over development. When reaching first emerges around 4 months of age, infants' reaches are inefficient: The hand speeds up and slows down multiple times as it takes a circuitous route to the target (von Hofsten, 1991). Historically, researchers believed that infants' jerky reaches resulted from over-correcting the hand's trajectory based on visual feedback, but later studies showed that reaching in infancy, unlike in adulthood, does not benefit from visual feedback about the hand relative to the target. Infants reach to targets with or without sight of the hand (manipulated by presenting a glowing target in a dark room) at the same age (Clifton, Muir, Ashmead, & Clarkson, 1993), and reaching kinematics are similar in conditions that permit or deny visual feedback (Babinsky, Braddick, & Atkinson, 2012b; Clifton, Rochat, Robin, & Berthier, 1994). Visual feedback begins to facilitate reaching around 15 months (Carrico & Berthier, 2008)—reaches in the dark are less straight and take longer to complete compared to reaches in the light. Like adults (Babinsky et al., 2012b; Connolly & Goodale, 1999), children reach more slowly without visual feedback (Babinsky, Braddick, & Atkinson, 2012a).

Do infants and children align gaze to objects to guide reaching in natural tasks? Natural reaching depends on coordinating movements of the whole body—the hands, eyes, and head need to be controlled within a stable base of postural support (Bertenthal & von Hofsten, 1998). Only recently has technology become available to measure infants' and children's eye movements during natural activity when the body is free to move; thus, little data are available on the development of visual guidance of natural manual activity. Prior work demonstrated that in a naturalistic play session, 14-month-old infants, like adults, reliably align gaze to objects while reaching (Franchak, Kretch, Soska, & Adolph, 2011). But laboratory studies suggest that visual feedback would not affect reaching kinematics at 14 months (Babinsky et al., 2012b). However, as in naturalistic studies of adult reaching, kinematics were not measured; thus, it is unknown whether aligning gaze to targets was related to infants' reaching performance.

Infants (as well as adults) may choose to look at objects for reasons other than guiding actions. Observers may look to objects to visually explore an object's properties (Soska et al., 2010), to engage in joint attention with a social partner (Yu & Smith, 2013), or simply because objects are interesting or salient. Comparing how reaching performance varies according to eye alignment would provide evidence about how vision and action are coordinated in children.

Current study

The current study has two main goals. The first goal is to test how the link between eye alignment and reaching performance identified in laboratory tasks might generalize to natural reaching. Although studies of natural manual activity found that observers tend to fixate objects (Hayhoe et al., 2003; Land et al., 1999), the role of object fixations is unclear because reaching performance was not assessed. Moreover, eye alignment was scored as a binary measure in prior naturalistic studies (e.g., did observers fixate the object or not) as opposed to a continuous measure as in experimental work (e.g., target eccentricity).

Thus, in the current study we addressed these limitations by correlating continuous measures of eye alignment and reaching performance during natural manual activity. Participants wore head-mounted eye trackers and motion trackers while manipulating objects on a table. We developed a novel procedure to segment reaching events from natural activity, providing a way to assess the eye alignment and reaching kinematics of each individual reach. In addition, we used computer vision algorithms to automatically detect objects and calculate the alignment of the eyes to the target object during each reaching event.

If eye alignment is related to reaching performance, we would expect participants to coordinate eye alignment with respect to reaching kinematics. We chose to focus on one particular aspect of reaching kinematics: the speed of the hand while reaching. Participants might look near the target when reaching rapidly, but when targets are viewed at greater eccentricities participants might reach more slowly.

The second goal of the current study was to compare how visually-guided reaching differs between children and adults. Naturalistic studies show that infants and adults reliably fixate objects while reaching, however, prior experimental work indicates that children might benefit from visual feedback only after 15 months. Thus, we tested 18- to 24-month-olds, an age group that should benefit from visual feedback, to determine how well experimental findings generalize to children's natural reaching.

Method

Participants

Twelve parent-child dyads participated in the study. Children were 18 to 24 months old (M = 20.8). Six children were female and 6 were male. Data were culled from a larger study that investigated parent-child interactions during object play, using the same procedure as in prior work (Yu & Smith, 2013). Dyads were selected if both the child and the parent provided accurate eye tracking and motion tracking data for the duration of the session to avoid data quality as a potential confound between ages. One dyad was excluded because the child did not reach for toys.

Apparatus

Participants sat on opposite sides of a small, white table; children sat in a high chair and parents sat on the floor. During each trial, three brightly colored objects (Figure 1) were placed on the table. Objects were approximately 290 cm^3 in size and could be grasped uni-manually by children. Participants were dressed in white clothing and the room was ringed with white curtains to facilitate computer vision

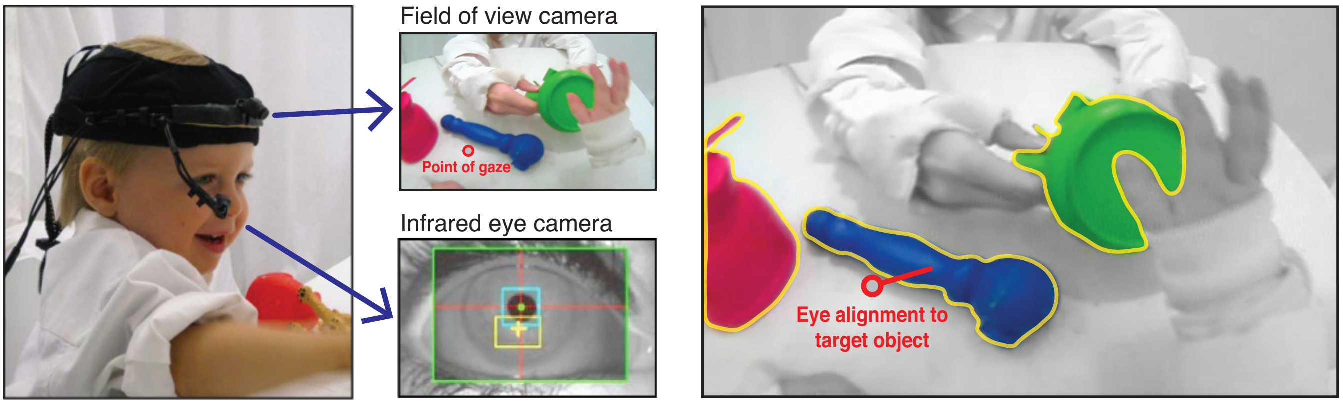

Figure 1: Child wearing head-mounted eye tracker (left). Miniature cameras record videos of the observer's eye and field of view (center) that are used to calculate the point of gaze (red circle). Computer vision algorithms automatically segment the colored objects from the white background (yellow outlines). In this example, the child is about to reach to the blue object. Eye alignment was defined as the distance between the center of the target object and the point of gaze (red line).

segmentation of the colored objects from the white background. Two third-person cameras recorded views of both participants and the table surface for later coding.

Each participant wore a head-mounted eye tracker (Franchak et al., 2011). As seen in Figure 1, each eye tracker consisted of two miniature cameras: An eye camera pointed in towards the face and recorded movements of the observer's eye, and a scene camera (100° diagonal field of view) pointed out and recorded the observer's egocentric, head-centered field of view. Participants fixated known locations in order to calibrate the eye tracker; Yarbus software (Positive Science) generated eye movement time series indicating the point of gaze within the observer's egocentric field of view (red circle in Figure 1). Eye movements were recorded at 30 Hz (smoothed over two successive samples) with a spatial accuracy of ~3° (for more details, see Franchak et al., 2011).

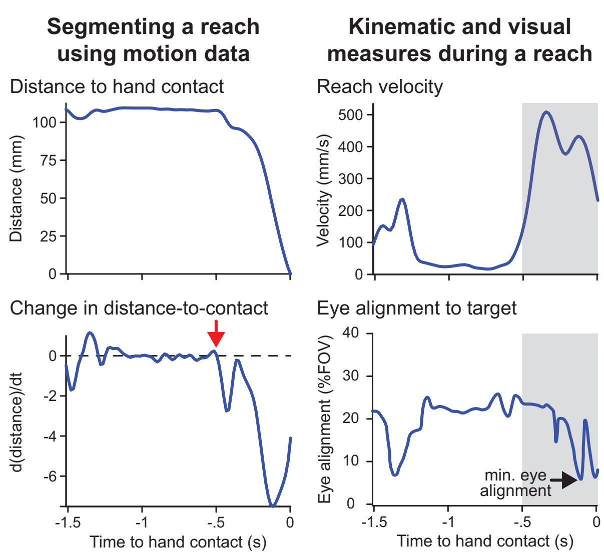

Figure 2: Example of a single reaching event over the 1.5 s before hand contact (0 on the x-axis). Left column shows segmentation based on distance-to-contact time series (top) and its derivative (bottom). Red arrow shows the resulting reach onset. Right column shows raw data for calculating reach velocity (top) and eye alignment (bottom) for the reaching period (shaded region). Black arrow shows minimum eye alignment during the reach.

In addition, participants wore magnetic motion sensors on the wrists of each hand. Each motion sensor tracked hand position with 6 degrees of freedom (Polhemus Liberty). Motion tracking data were recorded at 60 Hz and were synchronized with eye tracking data and third person videos. A second-order low-pass Butterworth filter with a 12 Hz cutoff frequency was applied to smooth motion tracking data as in previous research (Babinsky et al., 2012b).

Procedure

After the participants were fitted with recording equipment and completed the eye tracking calibration, parents were instructed to engage their children with the three provided objects in a manner of their choosing. No particular instructions were given about how parents should interact—the goal was to encourage a natural, free-flowing play session in which parents and children reached for and manipulated objects in the context of play. Depending on children's compliance, each experimental session lasted between 2 and 8 minutes. Object sets were replaced every 2 minutes to ensure children's continued interest.

Data analysis

In experimental studies of reaching, a common practice is to define reach onset when hand velocity exceeds a threshold value (e.g., Babinsky et al., 2012b). However, in natural action hands can move at high velocities for a variety of reasons (e.g., gesturing). Because there were no clearly defined reaching trials, analyzing eye-hand coordination required a method for segmenting reaching events from other manual behaviors. Our solution was to start by finding the end of a reaching event (contact with an object) and work backwards to determine when the reach began.

Coders used custom software to view third-person videos frame-by-frame and determined each time that a participant touched an object. We defined the time of reach offset based on the frame in which the hand made contact with an object (time 0 in Figure 2). The coder noted which hand made contact (right or left) and which object was contacted (red, green, or blue). To avoid counting accidental object touches as reaches, we excluded hand contacts less than .5 s.

Next, we extracted a time series of the hand's distance-to-contact (relative to the hand's position at reach offset) in the 1.5 s before reach offset using positional data from the motion tracker in three dimensions (Figure 2, top-left). We defined reaching as the period over which the hand's distance-to-contact decreased monotonically. The first derivative of the distance-to-contact time series (Figure 2, bottom-left) indicates change in the hand's position relative to its position at reach offset. When the derivative is negative, the hand's distance to contact is decreasing. We found the last zero-crossing of the distance-to-contact derivative time series and defined this time as reach onset (red arrow in Figure 2). Thus, we segmented reaching from the stream of natural activity based on a simple heuristic—the period during which the hand decreased in distance to its position at object contact.

For each reaching event we calculated two dependent measures that assessed eye-hand coordination: Average reach velocity and eye alignment to the target object. Average reach velocity was calculated by averaging instantaneous hand velocity at each time sample during the reach (Figure 2, top-right). Peak reaching velocity was also calculated but omitted from this report for the sake of brevity; the direction and significance of all reported results were the same for average and peak reaching velocity.

In order to calculate the eye's alignment to the target of the reach, we automatically detected the target object in the field of view video using a series of computer vision algorithms as described in prior work (Yu, Smith, Shen, Pereira, & Smith, 2009). Figure 1 illustrates the colored objects segmented from the background in the child's view. Next, we calculated the Euclidean distance between the point of gaze (red circle in Figure 1) and the geometric center of the target object. We defined this distance as eye alignment (red line in Figure 1). Eye alignment was expressed as a proportion of the diagonal of the field of view video and calculated for the entire duration of the reach (Figure 2, bottom-right).

Because actors do not typically keep their eyes fixed on a target for the entire duration of a reach and often look away before hand contact (Hayhoe et al., 2003; Land et al., 1999), we analyzed the *minimum* eye alignment value over the course of reaching. Smaller eye alignment minima mean that participants looked close to the target object at some point while reaching. Larger eye alignment minima indicate that participants never directed gaze near the target object. Figure 2 shows data from one reach. In this example, gaze became increasingly aligned to the object leading up to the moment of contact, resulting in a minimum eye alignment value of 7%. Note, eye alignment minima were rarely 0 because alignment was measured to the *center* of the target object, not the object boundary. We acknowledge that our eye alignment measure is not a perfect measure of viewing eccentricity due to camera parallax and lens distortion. However, it is a reasonable approximation to use in naturalistic situations where the head and eyes are free to move.

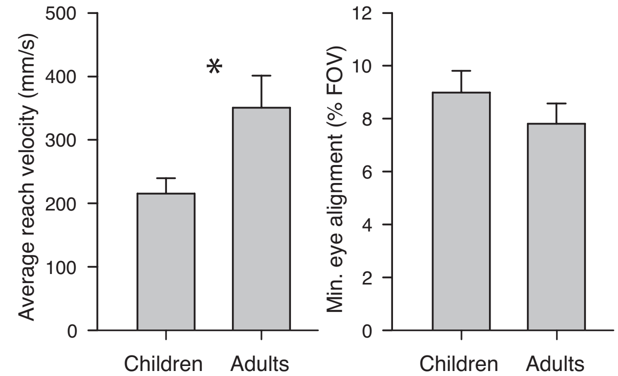

Figure 3: Average reach velocity and minimum eye alignment to the target object for children and adults.

Results

Overall, the dataset consisted of 316 reaching events (152 from children and 164 from adults). Figure 3 shows average reaching velocity and eye alignment to the object for children and adults. On average, adults (M = 350.9 mm/s, SD = 182.2) reached faster than children (M = 215.3 mm/s, SD = 80.9; $t(20) = -2.26$, $p = .035$). We found no significant difference in eye alignment between adults (M = 7.95%, SD = 2.73) and children (M = 8.99%, SD = 2.73; $t(20) = .893$, $p = .383$). As seen in Figure 4, both average reaching velocity and minimum eye alignment had wide ranges for both children and adults, and the ranges of each variable overlapped substantially between age groups. In other words, natural reaching in children and adults varied greatly in terms of reaching speed as well as viewing eccentricity when looking to the target object.

Next, we asked whether reaching speed and alignment were related in natural reaching for children and adults. We used linear generalized estimating equations (GEE) to model whether eye alignment predicted averaging reaching speed. As in a linear regression, GEE models can estimate how a predictor accounts for change in a dependent measure. Moreover, GEEs can estimate the overall group model based on each individual contributing a variable number of data points.

In our first model, we asked whether age group and reaching speed could predict eye alignment while reaching (choosing to predict reaching speed from eye alignment was arbitrary—the results hold if predicting eye alignment from reaching speed). We found no overall effect of age group (Wald's $\chi^2 = 2.02$, $p = .155$), as was expected based on the overall similarity in eye alignment between age groups. However, we found a significant effect of reaching speed (Wald's $\chi^2 = 7.34$, $p = .007$) and a significant age group by reaching speed interaction (Wald's $\chi^2 = 5.25$, $p = .022$).

To explore the interaction between age group and reaching speed, we asked if a link between reaching speed and eye alignment could be found in each age group separately. Thus, we calculated two GEE models—one for children and one for adults—that tested whether reaching speed predicted eye alignment. The scatterplots in Figure 4 show the relation between reaching speed and eye alignment

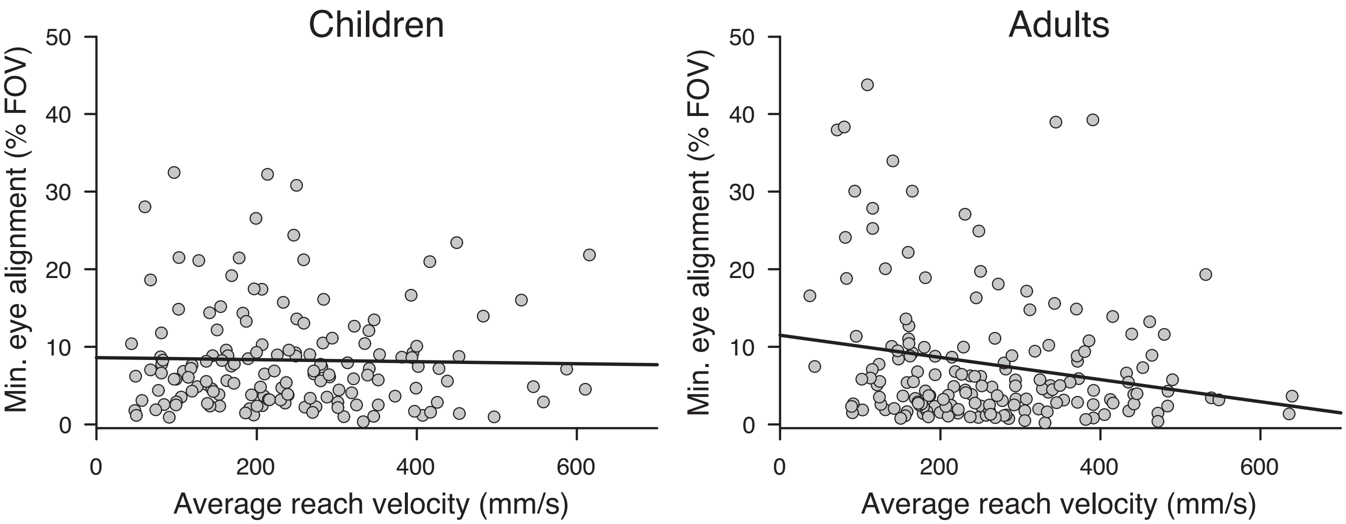

Figure 4: Relation between average reach velocity and minimum eye alignment to the target object. Each circle represents one reaching event. Solid black lines show GEE model predictions from each age group.

for each age group, plotting prediction lines from each model (solid black lines).

For children, we did not find a significant relation between reaching speed and eye alignment, B = -0.001 (Wald's χ^2 = .127, p = .721). In contrast, the adult model did find a significant link between reaching speed and eye alignment, B = -0.016 (Wald's χ^2 = 9.491, p = .002), suggesting that adults drove the main effect of reaching speed in the overall model. Adults reached more slowly when their eyes were not aligned to the target. Because of concern that extreme eye alignment values in adults might be responsible for the effects, we recalculated all three models excluding reaches where minimum eye alignment was greater than 30% of the field of view. However, the significance and direction of all results hold when those reaches were excluded.

Discussion

In summary, we tested whether children and adults coordinate eye alignment and reaching speed during natural reaching. Using a novel method for segmenting reaching events, we analyzed reaching in a naturalistic context—a child and parent playing with toys. Computer vision algorithms automatically detected the toys in each observers' egocentric view, and head-mounted eye tracking data were used to calculate how closely participants' aligned gaze to the target of their reach. Adults reached more slowly when they did not align gaze close to the target object. In contrast, we found no link between eye alignment and reaching speed for children.

These findings suggest that the effects of vision on reaching performance observed in laboratory tasks (Ma-Wyatt & McKee, 2006; Schlicht & Schrater, 2007; Sivak & MacKenzie, 1990) do generalize to more natural tasks. In those studies, experimental manipulation of target viewing affected reaching performance. In the current study, we found a correlation between reaching speed and eye alignment, both of which were selected by the participant. We make no claim about the causal direction between reaching speed and eye alignment. Possibly, participants adjusted reaching speed to match the quality of visual information during the reach, as in the laboratory studies. However, participants might have collected visual information depending on the requirements of the action they planned to perform (i.e., choosing to fixate the target when planning to reach rapidly). These possibilities are not mutually exclusive. In everyday life, adults must coordinate eye and hand movements to optimize multiple trade-offs in a complex landscape of tasks.

Although reaching speed and eye alignment were linked in adults, we found no such relation in 18- to 24-month-old children. One possibility is that children's use of visual feedback is still weak at the end of the second year. Indeed, although some studies find evidence that visual feedback facilitates reaching performance at 15 months (Carrico & Berthier, 2008), others failed to find an effect at 16 months (Babinsky et al., 2012b). Although an extreme manipulation of visual feedback may hinder infants' reaching (e.g., removing all visual cues about the hand relative tot he object), it is possible that a more subtle change in visual information (e.g., viewing the target in the periphery) might not be enough to significantly affect reaching at this age.

It is important to note, however, that the coordination between adults' reaching speed and eye alignment observed in the current study was fairly weak. Although the two variables were related, adults (and children) often executed slow reaches while looking closely to the target. In other words, participants might have collected better visual information than was necessary. Given the characteristics of the task—playing with brightly colored objects on a table—it should come as no surprise that participants (especially children) frequently attended to the objects. Indeed, other investigations of children's eye movements in object play show that children frequently attend to objects even at the expense of looking at other relevant stimuli, like faces (Franchak et al., 2011; Yu & Smith, 2013). Thus, the fact that we did not observe children coordinating reaching speed with visual information should not be taken as negative evidence: Children might have looked at objects even when it was not necessary. Indeed, the brightly colored toys on the white background, needed for the computer vision algorithms, may have been particularly salient. In future work, employing a task that draws attention away from action targets (Franchak & Adolph, 2010) or varying task difficulty would provide a stronger test.

The current study employed a new method for segmenting reaches. Typical laboratory studies control many aspects of the task, such as target size, target distance, starting position of the hand, and time allowed to complete the reach. How comparable was reaching in natural activity to reaching observed in the laboratory? Although we observed a wide range of reaching speeds (Figure 4), on average, reaching velocity in natural activity fell within the range of values reported in laboratory studies (for an overview of the literature, see Table 3 in Berthier & Keen, 2006).

Conclusion

Perceptual-motor development is more than simply learning how to use visual information to guide actions. Infants need to learn how to distribute limited visual resources to meet task demands. Many types of tasks—motor, perceptual, cognitive, and social—compete for visual attention. Adults are sensitive to visual-motor trade-offs and distribute eye gaze efficiently. In future work, investigating how children learn to select where to look in natural tasks will help us better understand the constraints on learning across all domains of development.

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