See and be seen: Infant-caregiver social looking during locomotor free play

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Abstract

Face-to-face interaction between infants and their caregivers is a mainstay of developmental research. However, common laboratory paradigms for studying dyadic interaction oversimplify the act of looking at the partner's face by seating infants and caregivers face to face in stationary positions. In less constrained conditions when both partners are freely mobile, infants and caregivers must move their heads and bodies to look at each other. We hypothesized that face looking and mutual gaze for each member of the dyad would decrease with increased motor costs of looking. To test this hypothesis, 12-month-old crawling and walking infants and their parents wore head-mounted eye trackers to record eye movements of each member of the dyad during locomotor free play in a large toy-filled playroom. Findings revealed that increased motor costs decreased face looking and mutual gaze: Each partner looked less at the other's face when their own posture or the other's posture required more motor effort to gain visual access to the other's face. Caregivers mirrored infants' posture by spending more time down on the ground when infants were prone, perhaps to facilitate face looking. Infants looked more at toys than at their caregiver's face, but caregivers looked at their infant's face and at toys in equal amounts. Furthermore, infants looked less at toys and faces less compared to studies that used stationary tasks, suggesting that the attentional demands differ in an unconstrained locomotor task. Taken together, findings indicate that ever-changing motor constraints affect real-life social looking.

Keywords: Eye movements, social interaction, joint attention, posture, face perception, play

Research Highlights

- Head-mounted eye tracking was used to measure gaze behavior in 12-month-old infants and their caregivers during fully mobile, naturalistic play to assess how perceptual-motor processes affect social looking (face looking, body looking, mutual gaze, and joint attention).
- Infants' and caregivers' posture affected rates of face looking and mutual gaze, indicating that greater motor costs were associated with decreases in looking.
- Caregivers mirrored infants' body posture by sitting down when infants were prone or sitting, affording infants (especially crawling infants) a better view of caregivers' faces.
- When freely mobile, infants' overall looking at toys and faces was lower compared to previous research that examined infants during stationary play.

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Few images are as poignant as a mother and infant gazing into each other's eyes. This prototypical image of mutual gaze between caregiver and infant is echoed in the face-to-face paradigms commonly used to study dyadic interaction. With their faces inches from each other, mother and infant engage in a time-locked "dance" of responsive facial expressions and coos (Jaffe, Beebe, Feldstein, Crown, & Jasnow, 2001; Yale, Messinger, Cobo-Lewis, & Delgato, 2003). Infants are acutely sensitive to the contingencies between their own behaviors and those of their mothers: The dance grinds to a halt if the contingencies are disrupted (Tronick, Als, Adamson, Wise, & Brazelton, 1978; Weinberg & Tronick, 1996). Infants become upset and try to reestablish the contingencies.

Face-to-face paradigms are also typical in studies of joint attention in which infants sit across from their caregivers and researchers record how each member of the dyad gathers visual information about the other and nearby objects. Infants monitor caregivers' gaze to jointly attend to objects (Bakeman & Adamson, 1984; Baldwin, 1993; Brooks & Meltzoff, 2005; Carpenter, Nagell, & Tomasello, 1998) or focus their visual attention on objects in caregivers' hands (de Barbaro, Johnson, Forster, & Deak, 2015; Deak, Krasno, Triesch, Lewis, & Sepeta, 2014; Yu & Smith, 2013, in press). Caregivers monitor infants' gaze to provide infants with timely information about places and objects that capture infants' attention (Bakeman & Adamson, 1984; Baldwin, 1991; Tomasello & Todd, 1983; Yu & Smith, 2013, in press).

Effects of motor costs on looking behavior

However, positioning infants and caregivers face to face reduces the motor costs of looking at a social partner's face. Looking is a motor action that typically involves movements of the head and body—not just the eyes (Gibson, 1979; Land, 2004; Land & Hayhoe, 2001; Pelz, Hayhoe, & Loeber, 2001). Motor actions take effort. Looking with only the eyes expends little effort but requires targets to be already in view, as in the classic face-to-face paradigm. Although infants experience such stationary contexts in everyday life, motor costs may affect looking in contexts where infants and caregivers are free to move their bodies. When a freely-moving social partner is out of view, observers must move their heads and bodies to look at their partner's face, and these motor actions require greater effort than merely moving the eyes. When infants explore the environment by crawling or walking, both infants' and caregivers' faces come in and out of each other's view. Both members of the dyad can produce behaviors that permit them to "see" and "be seen." Crawling infants can crane their necks up to bring a standing caregiver's face into view, and caregivers can crouch on the ground to better see their infant's face. But in unconstrained free play, will either or both members of the dyad incur the costs of performing such effortful behaviors to engage in face looking and mutual gaze?

Our primary aim was to test effects of motor cost on aspects of infants' and caregivers' social looking. We hypothesized that infants and caregivers do less *social looking*—looking at each other's faces or bodies or engaging in mutual gaze or joint attention—when looking entails a greater motor cost. Previous work assessed social looking of both infants and caregivers while dyads sat face to face across a table, and motor costs of social looking were not varied (Yu & Smith, 2013, in press). Although face-to-face interactions can involve motor costs such as deciding whether to tilt the head up to look at a partner's face or down to look at an object, these differences are subtle compared to situations where body position varies. Other work explicitly varied motor costs by encouraging infants to either crawl or walk over a raised platform, but we do not know whether social looking in this structured task generalizes to unconstrained free play, and caregivers' gaze was not measured (Kretch, Franchak, & Adolph, 2014). Eye gaze has been recorded in mobile infants during unconstrained play, but social looking to the caregiver's face was assessed only in response to infant-directed speech, motor costs were not assessed, and caregivers' social looking was not measured (Franchak, Kretch, Soska, & Adolph, 2011). Thus, to test the motor cost hypothesis for both infants and caregivers during unconstrained play, we needed to outfit both social partners with head-mounted eye trackers and record their looking behaviors "on the go."

We used body posture—standing or walking upright, sitting, crouching, or resting or crawling in a prone position—as a proxy for motor costs of face looking. As shown in Figure 1, changes in posture affect head position and how far the head can rotate up and down, thus altering the observer's viewpoint. Infants can see farther off in the distance and higher up while sitting and standing than while crawling. In contrast, the prone posture may complicate face looking. When prone, infants' field of view is dominated by the ground, and caregivers' faces are less often in view compared to sitting and standing (Frank, Simmons, Yurovsky, & Pusiol, 2013; Kretch et al., 2014). Face looking is more costly for infants in a prone posture than while sitting and standing because infants need to crane their head upward or change their body position to bring their caregiver's face into view (Kretch et al., 2014). Similarly, it should be easier for caregivers to view their infants' faces when caregivers crouch or sit at infants' eye level compared to when caregivers stand.

Reciprocally, the posture of the social partner affects the availability of that partner's face within the observer's field of view. When caregivers' posture was manipulated experimentally, caregivers' faces were in infants' view more often when caregivers were sitting compared to standing (Kretch et al., 2014). During free play, infants were less likely to respond to speech by looking at their caregivers' faces when caregivers stood than when they sat (Franchak et al., 2011). In other words, caregivers' decisions to sit or stand alter the costs for infants to look at caregivers' faces. A standing caregiver requires infants to rotate their heads to a greater degree to view the caregiver's face. Similarly, caregivers should have more difficulty looking at infants' faces when infants are prone with their faces pointed towards the floor than when infants sit or stand. Thus, we predicted that motor costs of body posture would affect face looking and, by extension, mutual gaze.

In turn, infants' developing locomotor skills affect their body posture. By the time infants can crawl on hands and knees, most can also sit up, pull to a stand, and "cruise" upright holding furniture for support (Adolph, Berger, & Leo, 2011; Atun-Einy, Berger, & Scher, 2012). The emergence of upright locomotion adds walking to the repertoire of skills. Although past work shows that walking infants have an advantage over crawling infants during social interactions—walkers make more social bids (Clearfield, Osborne, & Mullen, 2008; Karasik, Tamis-LeMonda, & Adolph, 2011) and interact more with caregivers (Clearfield, 2011)—previous work did not record eye movements. If walking infants spend less time prone and more time upright compared with crawlers, walkers would enjoy more frequent access to their caregiver's face. But, if crawling infants spend more time sitting than crawling, the disadvantage of their prone posture would be mitigated. However, previous work comparing crawling and walking infants did not measure how much time infants spend in different postures. Moreover, caregivers may affect the motor costs of looking through differences in their own posture. Caregivers of crawlers may spend more time down on the ground to better see (and be seen by) their crawling infants. Thus, the current study measured the real-time posture of both infants and caregivers and compared dyads of walking versus crawling infants.

Although it is likely that posture influences face looking and mutual gaze, other aspects of social looking, such as body looking and joint attention, may not be affected in the same way. As seen in Figure 1, whether crawling, sitting, or standing, some part of the partner's body is in view for each observer even when the face is not. Consequently, posture should affect the motor costs of face looking but not body looking. If observers want to look at a partner's face that is out of view, observers may elect to be less "choosy" and look at more easily accessible parts of the body rather than incurring the motor costs to look at the face. Thus, we predicted that infants' and caregivers' body looking would not depend on posture because posture does not elevate the motor costs—some part of the body is likely to be "low cost" regardless of posture. Likewise, if toys are placed on the ground or held in infants' or a seated caregivers' hands, infants' posture should not affect joint attention. However, caregivers' posture likely affects joint attention: Joint attention to objects should be easier when caregivers sit at infants' level but more difficult when caregivers are upright.

The role of context in social looking

Because this is the first study to document infant and caregiver social looking during locomotor free play, it is important to compare benchmark behaviors from prior studies to ask what changes across different contexts that infants experience in everyday life. Accordingly, our second aim was to determine how findings from prior investigations of social looking in stationary tasks compare to unconstrained locomotor play. Previous work showed that while dyads were stationary and sitting face to face at a table or on the floor, infants look more at toys (60-70% of the time) than at parents' faces (10-15% of the time) (Deak et al., 2014; Yu & Smith, 2013). In contrast, caregivers spend more time looking at infants' faces (37-80% of the time) compared to toys (17-48% of the time). Mutual gaze occurs 10-13% of the time—limited by the brief amount of time that infants spent looking at parents' faces. Periods of joint attention to objects (33%) are more frequent than periods of mutual gaze (Yu & Smith, 2013).

Stationary play might focus the dyad to attend only to nearby targets. When free to move in a larger, more complex environment, a more diverse array of objects, places, and activities compete for infants' and caregivers' visual attention. Looking behaviors are economical: Infants, children, and adults look at things that are relevant to their current goal and rarely expend the extra effort to look elsewhere (Franchak & Adolph, 2010; Kretch & Adolph, 2017; Land & Hayhoe, 2001; Pelz et al., 2001). Following this logic, we hypothesized that both social looking and overall toy looking would be depressed during mobile free play compared to stationary, seated play because mobility increases competition for attention (e.g., guiding locomotion, exploring different parts of the room). Regardless, we expected to replicate the basic pattern of results: Infants should look longer at toys compared to faces, and caregivers should look longer at faces compared to toys.

Current Study

To examine effects of motor costs on social looking, we outfitted infants and their caregivers with head-mounted eye trackers as they played freely in a large laboratory playroom.

To our knowledge, this is the first study to exploit this technology with fully mobile infant-caregiver dyads in naturalistic interactions. We obtained four indices of social looking—face looking, body looking, mutual gaze, and joint attention—to test our predictions that motor costs associated with different postures would affect face looking and mutual gaze but spare body looking and joint attention. We also predicted that infants' locomotor status—whether a crawler or walker—would affect how infants and caregivers distribute their time in different postures, which, in turn, would affect the motor costs of face looking. Finally, to compare gaze behavior during mobile free play to past investigations where dyads sat in one place, we scored toy looking in addition to the indices of social looking. We predicted that looking would be drawn away from both toys and faces during unconstrained free play compared to contexts where dyads were stationary. Measuring the distribution of visual attention in an unstudied naturalistic context will broaden our knowledge about everyday looking behavior.

Method

Participants

Seventeen 12-month-olds (range = 11.8-12.4 months) and their caregivers participated. Families were recruited from maternity wards of local hospitals in the New York City metropolitan area and received souvenirs of participation. Families were predominantly White and middle-class. Locomotor status was measured from a structured interview with the caregiver as in prior work (Adolph, Vereijken, & Shrout, 2003) and was confirmed by observing whether infants could crawl and walk in the lab. Eight infants (5 boys, 3 girls) crawled on their hands and knees as their typical form of locomotion (M = 4.7 months of crawling experience, range = 2.6-6.8 months); none could walk independently, but all could sit and 7 could cruise upright along furniture. Nine infants (4 boys, 5 girls) could walk (M = 1.2 months of walking experience, range = 0.6-2.3 months). Thirteen infants (7 crawlers, 6 walkers) participated with their mothers, and four (1 crawler, 3 walkers) participated with their fathers. One mother of a walker did not contribute eye-tracking data due to equipment failure. Data from 7 additional infants were excluded: 4 infants became too fussy to complete the study, 3 repeatedly removed the eye tracker, and 1 had eye-tracking data that could not be calibrated due to poor camera placement.

Head-mounted eye tracking

Wearable eye-tracking equipment. As seen in Figure 2, infants and caregivers each wore a Positive Science head-mounted eye tracker (Kretch & Adolph, 2015). The infant eye tracker consists of two small cameras mounted on a Velcro-covered band: The *scene camera* points straight out from the band to capture the scene in front of the infant (54.4° × 42.2° field of view), and the *eye camera* extends out via a flexible wire and points in to record the infant's eye movements. The band attaches to a fitted cap so that the eye camera faces the right eye and the scene camera sits above the right eyebrow. Infants also wore a harness with straps that were held by an experimenter during the session, which prevented injury from face-first falls (Franchak et al., 2011). The adult eye tracker contains the same two cameras mounted on eyeglass frames. The equipment was light and comfortable to wear, allowing both infants and caregivers to move freely and to switch between postures with ease.

Video capture. To capture the four video streams (infant's scene, infant's eye, caregiver's scene, and caregiver's eye), we used two video capture methods simultaneously. Infants' videos were delivered via a cable to a laptop computer, where they were captured and synchronized using Live Capture software (Positive Science). To permit full mobility while infants were tethered to the laptop, the experimenter following behind the infant carried the laptop in a backpack. The videos were streamed wirelessly from the laptop to a second computer running Yarbus software (Positive Science) to allow online monitoring of eye and scene videos. Caregivers' videos were each captured separately to digital camcorders, which they wore in a backpack.

Calibration and video processing. Infants were outfitted with the vest, cap, and eye tracker, and seated 1.5 m away from a white display board with cutout windows. An assistant inserted noisy, salient toys in the windows to attract infants' attention to different calibration targets across visual space. Caregivers were outfitted with their eye tracker and backpack, and were instructed to fixate nine targets on a similar display board held at eye level. After the session, calibration was performed in Yarbus software by marking the target locations on the appropriate video frames. The software then calculates frame-by-frame point of gaze within the scene camera video. The software produced processed videos for infant and caregiver with the point of gaze indicated on each video frame by a 4° radius circular cursor (Figure 2).

We estimated the accuracy of the eye movement data for each observer. We selected 20 frames where observers looked at a calibration target (5 consecutive frames for 4 separate targets). Using custom Matlab software, we calculated the distance between the point of gaze and the calibration targets in pixels. Based on the eye tracker field of view, we converted the pixel-based accuracy measure to degrees and determined that accuracy was $M = 1.55°$ ($SD = 0.57$) for infants and $M = 0.85°$ ($SD = 0.33$) for caregivers.

Free play

After calibration, caregivers were instructed to play with their infants in the lab playroom. Sessions lasted 5 to 15 minutes, but only the first 5 minutes of data from each dyad were coded. Caregivers and infants could go anywhere in the room and play with any of the available toys. The room was 4.5 m × 6 m and contained a couch, 2 small raised platforms and stairs for climbing, and six toys: ball, jingling apple, musical saxophone with song buttons, stuffed dog, xylophone, and toy car. The entire room was filmed from a fixed overhead camera; an assistant recorded infants' activity with a handheld camera.

Data processing

The four videos (infant eye-tracking, caregiver eye-tracking, overhead camera, and handheld camera videos) were synchronized into a single composite video using Final Cut Pro. Composite videos are available on the Databrary library (databrary.org). All variables were scored frame-by-frame from the composite video using Datavyu software (www.datavyu.org). A primary coder scored 100% of the data, and a second coder scored 33% of each dyad's data to assess inter-rater reliability; coders agreed on > 92.4% of video frames for all variables (*kappas* = .75-.99).

Infant posture. Infants' posture was scored for each video frame as either upright, prone, or sitting (Figure 1). Posture was scored based on body position only; infants could be stationary or in motion in each of the postures, but we did not code whether infants were in motion. While *upright,* infants stood, cruised, or walked and they could be supported (by caregiver or furniture) or unsupported. While *prone,* infants were on hands and knees, hands and feet, or lying on their belly. *Sitting* included legs-out sitting with the bottom on the floor, kneeling with legs tucked under the bottom, or short-sitting on a raised platform with the bottom on the platform and legs hanging down. Portions of the session where infants were held or carried by their caregivers were not analyzed because they comprised <1% of the data.

Caregiver posture. Caregivers' posture was scored for each video frame as upright or down (see Figure 1). Caregivers were *upright* if they were standing or walking with their feet on the floor and their knees relatively straight. Caregivers were *down* if they were squatting (knees flexed more than 90°), sitting, kneeling, on hands and knees, or lying down.

Face looking, body looking, and toy looking. Both caregivers' and infants' eye-tracking videos were scored for face looking, body looking, and toy looking. Looking at *faces* was scored any time the circular cursor (white circles in Figure 2) contained any part of the partner's face, between the chin and the hairline; hair and the back of the head were not included. A potential concern is that the smaller field of view of the scene camera compared to those used in prior work (e.g., Yu & Smith, 2013) could lead to under-reporting of looking. This is unlikely, however, because infants (like adults) keep their eyes relatively centered in view (within the bounds of the scene camera) most of the time (Bambach, Smith, Crandall, & Yu, 2016). As an additional precaution, we assumed infants' gaze to be directed at the caregiver's face if both the gaze location and the face were above the boundary of the video frame.

Looking at *bodies* was scored when the circular cursor intersected with any part of the body, excluding the face. In addition, body looking was scored if the gaze cursor fell on a toy held in the hands of the social partner. Thus, body looking included all person-directed looking except face looking. *Mutual gaze* was calculated when both the infant and caregiver looked at each other's faces at the same time. Looking at *toys* was scored any time the circular cursor contained any part of one of the six toys and did not contain the partner's face. The same video frame could be counted as both toy and body looking if gaze was directed at a toy held by the caregiver. *Joint attention* was calculated when both the caregiver and infant looked at the same toy at the same time.

One potential concern with using a head-mounted eye tracker is that parallax errors resulting from the physical offset between the observer's eye and the scene camera mean that calibration accuracy varies according to target distance. Accuracy is best for targets at the same distance as the calibration targets (in the current study, 1.5 m), and declines for targets closer and farther. Prior work using similar equipment and calibration procedures estimates parallax errors to be within 2° when viewing targets 0.6-3 m away (Li, 2006; Mardanbegi & Hansen, 2012), which accounts for the majority of the session because infants and caregivers were typically in close proximity.

Another possible concern is that spatial error in the eye-tracking system might lead to under-reporting of looks to different targets and that marginally worse accuracy in infants compared to adults could lead to under-reporting of looks in infants compared to adults. Using the large, 4°-radius cursor to define looks ensured that errors in coding of looking were more liberal (included more events) than conservative (excluded potential events) and protects against errors resulting from parallax and calibration. Finally, because targets moved in depth relative to observers, targets changed in visual angle (a face viewed from 1 m and 3 m provide different percepts). We did not attempt to distinguish between near and far targets, but simply report whether targets were within the cursor and thus were most likely the focus of overt attention.

Proportions of time spent looking at faces, bodies, and toys were calculated for each observer relative to the amount of usable eye-tracking data from that observer, excluding times when the pupil was not correctly detected or the gaze cursor was outside the boundary of the field of view (frames where the infant was assumed to be looking at the caregiver's face above the video frame boundary were counted as useable data). On average, infants provided usable eye tracking data on *M* = 90.6% (*SD* = 7.6) of frames. Excluding the caregiver for whom no eye tracking data were available, usable data were available for *M* = 93.6% (*SD* = 3.4) of frames for caregivers. Usable data for dyads, when both the infant and caregiver had usable eye tracking data at the same time, averaged *M* = 85.0% (*SD* = 8.1), and was used for calculating mutual gaze and joint attention.

Finally, we tested whether observed rates of mutual gaze and joint attention in each posture were higher than would be expected by chance overlaps between infant/caregiver face looking (mutual gaze) and infant/caregiver toy looking (joint attention). To do so, we created 1,000 time-randomized baselines by realigning the sequence of caregiver eye movements relative to the infant eye movements (Franchak, Heeger, Hasson, & Adolph, 2016). This procedure preserved the overall looking rates while breaking the synchrony between infant and caregiver. We recalculated mutual gaze and joint attention for realigned sequences to create null distributions for each dyad and measure. Mutual gaze/joint attention was significantly greater than chance for a dyad if the observed value (when synchronized) exceeded 95% of the realigned baselines (α = .05).

Data analyses. Effects of motor costs on social looking were tested with ANOVAs. Mauchly's and Levene's tests for each analysis did not indicate violations of sphericity or homogeneity of variance. Degrees of freedom varied slightly between ANOVAs due to some dyads dropping out of analyses in cases where the dyad did not contribute data (e.g., an infant who never was prone could not be tested for within-subject effects of infant posture). Sidak corrections were used to adjust for multiple pairwise comparisons. Cochran's Q tests (Cochran, 1950) for comparing proportions between matched samples determined whether the number of dyads who had greater-than-chance levels of mutual gaze and joint attention varied according to posture.

Results

Effects of motor costs on social looking

The primary analyses tested effects of infant and caregiver posture on each of the four indices of social looking: face looking, body looking, mutual gaze, and joint attention.

Social looking by infant posture. As predicted, *face looking* was moderated by infants' posture. When infants were prone, they were less likely to look at caregivers' faces and caregivers were less likely to look at infants' faces (Figure 3A). Face looking was similar between sitting and upright postures. Perhaps the most striking aspect of Figure 3A is how little infants looked at caregivers, regardless of posture. Infants looked at their caregiver's face less than 5% of the time, whereas caregivers looked at their infant's face more than 30% of the time. A 3 (infant posture: prone, sitting, upright) × 2 (observer: infants, caregivers) ANOVA on face looking confirmed main effects of posture and observer (Table 1). Pairwise comparisons indicated that both infants and caregivers looked at their partners' faces less often when infants were prone compared to when infants were upright (infants: $p = .034$, $d = 0.88$; caregivers: $p = .024$, $d = 0.95$) and sitting (infants: $p = .012$, $d = 1.13$; caregivers: $p = .027$, $d = 0.83$), but face looking did not differ between upright and sitting (infants: $p = .99$, $d = 0.03$; caregivers: $p = .98$, $d = 0.13$).

Mutual gaze related to infants' posture in a similar way. Although mutual gaze was rare (overall, $M = 2.5\%$, $SD = 1.7$), it was less frequent when infants were prone ($M = 0.24\%$, $SD =$

0.63) compared to when infants were sitting (*M* = 2.42%, *SD* = 2.62) or upright (*M* = 3.61%, *SD* = 4.85). A one-way ANOVA on mutual gaze confirmed a main effect of infant posture (Table 1). Pairwise comparisons indicated that mutual gaze while infants were prone was less frequent than while sitting (*p* = .015, *d* = 1.09) or upright (*p* = .059, *d* = 0.82). Mutual gaze did not differ between sitting and upright (*p* = .824, d = 0.21).

For each dyad in each posture, we tested whether the observed rate of mutual gaze was significantly greater than would be observed by chance. Mutual gaze exceeded chance levels for 6/16 dyads while sitting (37.5%), 9/16 while upright (56.3%), and 1/15 while prone (6.6%). A Cochran's Q test confirmed that the proportion of dyads with greater-than-chance rates of mutual gaze was greater for sitting and upright compared to prone, $\chi^2(2) = 7.09$, *p* = .038.

In contrast, *body looking* related to infants' posture for caregivers but not for infants. Figure 3B shows that rates of looking to the caregiver's body were similar across postures for infants (15.3% of the time overall), but that caregivers looked at infants' bodies more often when infants were prone (60.0%) compared to when infants were upright (37.5%) or sitting (41.9%). A 3 (infant posture) × 2 (observer) ANOVA on body looking confirmed a main effect of observer and a significant posture × observer interaction (Table 1). Pairwise comparisons showed that the amount of time caregivers spent looking at infants' bodies was greater for prone compared to upright (*p* = .01, *d* = 0.84) and sitting (*p* = .02, *d* = 0.97) but that sitting and upright did not differ (*p* = .69, *d* = 0.28).

Finally, *joint attention* was related to infant posture, but followed a different pattern than face looking and mutual gaze. Overall, joint attention occurred *M* = 17.1% of the time (*SD* = 13.7). However, joint attention was most common while infants sat (*M* = 21.75%, *SD* = 19.44) compared to while prone (*M* = 9.93%, *SD* = 0.11) or upright (*M* = 11.45%, *SD* = 10.1). A one-way ANOVA confirmed a main effect of infant posture on joint attention (Table 1). Pairwise comparisons showed more frequent joint attention while sitting compared to prone (*p* = .03, *d*

= 0.87) and upright (p = .049, d = .946), but joint attention did not differ between prone and upright postures (p = .924, d = 0.15). However, joint attention exceeded chance levels (compared to re-aligned baselines) for the same proportion of dyads while sitting and upright (73%). Although greater-than-chance joint attention was rarer while prone (46.7%), the three proportions did not significantly vary, $\chi^2(2) = 2.67$, p = .30.

Social looking by caregiver posture. *Face looking* was moderated by caregivers' posture. Infants looked at caregivers' faces more when caregivers sat or crouched down compared to when caregivers stood upright (Figure 3C). Similarly, caregivers looked more often at infants' faces while down compared to while upright. A 2 (caregiver posture: down, upright) × 2 (observer) ANOVA on face looking revealed main effects of caregiver posture and observer moderated by a significant posture × observer interaction (Table 1), indicating that the posture effect on caregivers' face looking was greater than the posture effect on infants' face looking.

Similarly, *mutual gaze* occurred more frequently when caregivers were down (M = 2.95%, SD = 1.53) compared to when caregivers were upright, M = 0.37%, SD = 0.81 (Table 1), and a marginally greater proportion of dyads exceeded chance levels of mutual gaze while caregivers were down (40%) compared to upright (6.7%), $\chi^2(1) = 3.57$, p = .059.

Body looking was not significantly related to caregivers' posture (Figure 3D), indicating that the effect of caregiver's posture was restricted to faces. A 2 (caregiver posture) × 2 (observer) ANOVA on body looking revealed only a main effect of observer, confirming that caregivers looked more often at infants' bodies than infants looked at caregivers' bodies (Table 1).

Finally, *joint attention* occurred more frequently when caregivers were down (M = 17.26%, SD = 14.17) compared to upright (M = 7.81%, SD = 8.77). A one-way ANOVA confirmed a significant main effect of caregiver posture on joint attention (Table 1). However, joint attention was not better coordinated depending on caregiver posture: 53% of dyads exceeded chance levels of joint attention when caregivers were down on the ground compared to 47% with caregivers upright, $\chi^2(1) = 3.57$, $p = .763$.

Locomotor status. None of the four indices of social looking varied according to infants' locomotor status. Face looking and body looking were similar for crawling and walking infants and caregivers of crawling and walking infants (Table 2A); 2 (locomotor status: crawler, walker) × 2 (observer) ANOVAs on face and body looking revealed only main effects of observer (Table 2B). Moreover, mutual gaze and joint attention were similar for walking dyads and crawling dyads (Table 2A) and one-way ANOVAs found no significant effects of locomotor status (Table 2B).

Real-time posture depended on locomotor status. At first glance, it was puzzling that social looking was similar for crawlers and walkers despite significant effects of real-time posture. However, any potential effects of locomotor development depend on how they are expressed through posture. As shown in Figure 4A, crawlers were prone (M = 25.6%, SD = 15.7) more often than walkers (M = 5.3%, SD = 5.8), $t(15) = 3.64$, $p = .002$, $d = 1.88$. Walkers spent more time upright (M = 69.9%, SD = 18.4) compared to crawlers (M = 28.6%, SD = 15.0); $t(15) = -5.04$, $p < .001$, $d = 2.6$. And crawlers spent more time sitting (M = 45.9%, SD = 16.5) compared to walkers (M = 24.9%, SD = 14.8); $t(15) = 2.79$, $p = .014$, $d = 1.44$. Every infant spent some time upright and sitting regardless of locomotor status, and every crawler spent some time prone, but 2 walkers were never prone. Although crawling infants were prone more than walking infants, the lower overall frequency of the prone posture compared to other postures might account for the lack of differences in social looking between crawlers and walkers.

Both groups of caregivers spent most of the time crouched down or sitting on the floor (Figure 4B), but these postures did not prohibit them from moving. Caregivers followed infants around the room (by scooting, crawling, and walking) and stayed close by as infants explored various objects and locations. Caregivers' posture was weakly related to infants' locomotor status: Caregivers of crawlers spent marginally more time down on the floor (*M* = 90.6%, *SD* = 11.2) compared to caregivers of walkers (*M* = 71.5%, *SD* = 24.3), $t(15) = 2.03$, $p = .06$, $d = 1.05$. Three caregivers of crawlers and one caregiver of a walker never stood upright during the play session.

Caregivers' posture was related to infants' posture: Caregivers of infants who spent more time upright spent more time upright themselves, even after controlling for infants' locomotor status. We conducted a hierarchical linear regression on the proportion of time caregivers spent upright, entering locomotor status followed by infants' time spent upright as predictors. Infants' locomotor status accounted for 21.9% of the variance in caregivers' upright time, and the model was marginally significant, $F(1, 15) = 4.22$, $p = .06$. Adding infants' time spent upright accounted for an additional 23.6% of the variance (R^2 change $p = .028$) and resulted in a significant model, $F(1, 14) = 5.84$, $p = .01$. In the final model, infants' time spent upright ($p = .03$), but not infants' locomotor status ($p = .629$), was a significant predictor of how long caregivers were upright.

Overall looking to toys and faces

As in past work with stationary dyads (Deak et al., 2014; Yu & Smith, 2013), infants spent longer looking at toys compared to caregivers' faces (Figure 5). However, looking at both toys and faces was about half as frequent in the current study when dyads were unconstrained: Infants looked at toys *M* = 37.5% (*SD* = 21.4) of the time and at caregivers' faces *M* = 4.7% (*SD* = 2.8) of the time whereas in studies where infants were stationary, they looked at toys 60-70% of the time and to faces 10-15% of the time. Caregivers looked at toys (*M* = 30.6%, *SD* = 14.2) for about the same amount of time that they looked at infants' faces (*M* = 31.5%; *SD* = 9.3). Both values fall within the ranges reported in tasks where dyads were stationary (37-80% for faces, 17-48% for toys), but in stationary tasks, caregivers spent more time looking at faces compared to toys. A 2 (target: faces, objects) × 2 (observer: infants, caregivers) ANOVA on looking time revealed main effects of target, $F(1, 15) = 13.37$, $p = .002$, partial-$\eta^2 = .47$, and observer, $F(1, 15) = 29.61$, $p < .001$, partial-$\eta^2 = .66$, moderated by an observer × target interaction, $F(1, 15) = 44.81$, $p < .001$, partial-$\eta^2 = .75$. Pairwise comparisons confirmed that infants looked longer at toys than faces ($p < .001$, $d = 0.77$) and caregivers spent similar amounts of time looking at toys and faces ($p = .859$, $d = .05$). Infants and caregivers engaged in mutual gaze ($M = 2.5\%$, $SD = 1.7$) and joint attention ($M = 17.1\%$; $SD = 13.7$) less often than in stationary tasks (Deak et al., 2014; Yu & Smith, 2013).

Discussion

This study was the first to capitalize on head-mounted eye tracking to measure social looking of both infants and caregivers while dyads were engaged in unconstrained play. We found support for the motor cost hypothesis: Face looking in infants and caregivers and mutual gaze in dyads decreased when the postural context made looking more costly (prone infants and upright caregivers). Our prediction that body looking would be unaffected by posture was borne out for infants but not for caregivers, who looked more often at infants' bodies when infants were prone and their faces were difficult to view. We did not predict joint attention to differ according to infant posture, however, we found that joint attention was more frequent during periods of infant sitting. As expected, joint attention increased when caregivers were down on the ground.

As predicted, the amount of time spent in different postures varied with infants' locomotor status. Walkers spent more time upright compared to crawlers, and crawlers spent more time sitting and prone compared to walkers. However, both walkers and crawlers were infrequently prone and spent most of their time in upright and sitting postures that were more conducive to face looking. Furthermore, caregivers' posture mirrored infants' posture—when infants spent more time upright, so did caregivers. Consequently, no overall differences were found in social looking between crawlers and walkers.

There was a sharp asymmetry between infants' and caregivers' looking. As in past work, infants rarely looked at caregivers' faces and frequently looked at toys (Deak et al., 2014; Yu &

Smith, 2013). In contrast, caregivers looked frequently at infants' faces and at toys. However, overall rates of looking at both toys and faces were reduced in the current study compared to past studies that used stationary tasks, suggesting that the mobile play context changed demands on attention.

Effects of motor costs on social looking

The current study adds to a growing body of research demonstrating embodied influences on infants' visual experiences (Franchak et al., 2011; Frank et al., 2013; Kretch et al., 2014) and their participation in dyadic and triadic interactions (de Barbaro et al., 2015; Deak et al., 2014; Fogel, Dedo, & McEwen, 1992; Fogel, Messinger, Dickson, & Hsu, 1999; Karasik et al., 2011; Karasik, Tamis-LeMonda, & Adolph, 2014; Wiesen, Watkins, & Needham, 2016; Yoshida & Smith, 2008; Yu & Smith, 2013, in press). Previous work showed that infants' posture predicts how often faces are in the field of view of a head-mounted camera (Frank et al., 2013; Kretch et al., 2014). The current study goes a step farther by showing that infants' and caregivers' posture predicts how often they direct their gaze at faces and bodies.

For infants, the prone posture hindered visual access to their caregiver's face. However, this does not imply that the prone posture is categorically bad for social looking and that sitting and standing are good. The motor costs of looking depend on the physical location of the target relative to the observer's viewpoint. We found that rates of infant looking at caregivers' bodies (a larger target compared to the face) was unaffected by either partner's posture. Likewise, toys on the floor or important features of the ground surface are easily seen while crawling (Adolph, 1997; Kretch et al., 2014); infants fixate obstacles more often when crawling over them compared to when they are walking over them (Franchak et al., 2011). We found no disadvantage of the prone posture for joint attention compared to an upright posture; toys could be easily viewed in either posture. However, joint attention was more frequent when sitting compared to both prone and upright, possibly because prone and upright postures were associated with locomotor rather than stationary play.

Previous research on the effects of posture on visual experience focused solely on the infant's posture and the infant's view of the world (Frank et al., 2013; Jayaraman, Fausey, & Smith, 2015; Kretch et al., 2014). A unique aspect of the current study was that we simultaneously measured infants' and caregivers' posture and looking behaviors. The face contains the observer's eyes *and* serves as a social stimulus for the partner. Thus, the positions that negatively affected visual access to the partner's face did so for both members of the dyad: Infants looked less often at caregivers' faces when caregivers stood, and caregivers looked less often at infants' faces when infants were prone. The same was not true for body looking because bodies are easily viewed by either partner for any combination of postures, with one exception: Caregivers looked more often at infants' bodies while infants were prone compared to the other postures. Most likely, increased looking at infants' bodies resulted from difficulty viewing prone infants' faces.

Role of motor development

The emergence of walking is linked with advances in cognitive, social, and language development (Adolph & Robinson, 2015; Adolph & Tamis-LeMonda, 2014; Biringen, Emde, Campos, & Applebaum, 1995; Clearfield, 2011; Karasik et al., 2011, 2014; Walle & Campos, 2014). One explanation for these developmental advances is that walking infants have a better viewpoint to see important stimuli, such as caregivers' faces, compared to infants who can only crawl. The current study highlights the importance of measuring both developmental abilities and real-time behavior because the downstream effects of locomotor abilities can only emerge in real time. We found no overall difference in face looking between crawlers and walkers despite differences in looking between prone (crawling) and upright (walking) postures. This apparent discrepancy is partly explained by the fact that crawlers spent most of their time in upright and sitting positions, providing them with an adequate view of faces. Other studies also showed that walking infants walk, and are thus upright, more than crawling infants crawl, and are thus prone (Adolph et al., 2012). When crawlers do crawl, they switch to a sitting position after a few crawling steps, possibly to gain a better view of their surroundings (Kretch et al., 2014; Soska, Robinson, & Adolph, 2015). Another possible consequence of walkers spending more time walking than crawlers do crawling is a difference in proximity to caregivers. Walkers may spend more time exploring their surroundings and more time away from caregivers (Thurman & Corbetta, in press). In contrast, crawlers play closer to caregivers, giving them more opportunity to look at caregivers' faces.

A second explanation for why face looking did not differ by locomotor status is that caregivers' posture was contingent on infants' posture. Because crawling infants spent more time prone, their caregivers spent more time down on the floor, which in turn provided crawling infants with more opportunities to view caregivers' faces. Perhaps caregivers wished to gain better access to their children's faces or to make their faces more available to infants. Or perhaps caregivers simply responded to infants' play. Caregivers of crawlers may have sat more because crawlers preferred to play with toys from a sitting position; in contrast, caregivers of walking infants had to contend with their infants careening from one place to the next, requiring caregivers followed infants in an upright (walking) position.

Although face looking was similar for crawlers and walkers, new motor skills may elicit differences at other points in development. Other motor skills—such as the ability to lift the head up while prone, sit independently, or pull to a stand—may change how infants experience the visual world. Motor development may explain changes in visual experience over longer timescales, such as the decreasing availability of faces in view from birth to 24 months (Fausey, Jayaraman, & Smith, 2016; Jayaraman et al., 2015). Lying supine results in greater looking to the caregiver's face compared to upright or sitting postures (Fogel et al., 1992; Fogel et al., 1999). Three-month-olds spend significant time in supine and reclined postures, but those postures give way to sitting, prone, and upright postures as infants gain new motor skills over the first year (Franchak, in prep), which may in turn lead to lower frequency of faces in view.

Future work that uses eye tracking to measure social looking across a wider range of ages and postures will help determine the influence of motor development on infants' visual experiences.

Allocating visual attention

Many theories of social-cognitive development stress the importance of infants looking at caregivers' faces to engage in gaze following, joint attention, and social referencing (Brooks & Meltzoff, 2005; Carpenter et al., 1998; Mundy & Newell, 2007). But how much infants can learn through such mechanisms depends on how often infants actually look at caregivers' faces. In the current study, infants prioritized looking at toys (37.5% of the time) over caregivers' faces (4.7% of the time). Similar discrepancies were found between toys and faces when infants played while sitting still at a table (Yoshida & Smith, 2008; Yu & Smith, 2013) or on the floor (Bakeman & Adamson, 1984; Deak et al., 2014), suggesting that infants' preference for looking at toys over faces in the current study is not simply due to postural constraints. Visual-manual exploration of objects might bias infants to angle their heads down, which would put caregivers' faces out of view even while sitting (Bambach, Franchak, Crandall, & Yu, 2014).

A second reason why infants rarely look at caregivers' faces is that they do not need to seek information from caregivers' faces to establish shared reference. Despite low rates of face looking, caregivers and infants were actively engaged with each other and jointly attended to the same toys during 17% of the session. Yu and Smith (2013, in press) argued that hands are a better cue for another person's attention compared to the face and showed that looking to hands often precedes joint attention. Other work showed that infants respond to caregivers' speech more often by looking at caregivers' hands rather than their faces (Franchak et al., 2011). Similarly, infants in the current study looked more often at caregivers' bodies (which included hands) compared to their faces. Furthermore, caregivers have ways of establishing shared reference that do not rely on infants: They initiate joint attention by looking at objects to which infants are already attending (Bakeman & Adamson, 1984; Baldwin, 1991; Tomasello & Todd, 1983; Yu & Smith, in press) and redirect infants' gaze to objects by bringing them into infants' view and/or gesturing (Wiesen et al., 2016; Zukow-Goldring & Arbib, 2007). We found that caregivers frequently looked at both infants' faces and at toys, suggesting that caregivers monitored infants' gaze direction towards objects to better engage in triadic play.

Of note, our focus on unconstrained locomotor play resulted in less overall looking to both toys and faces compared with stationary play (Deak et al., 2014; Yu & Smith, 2013). More than half of the time, infants looked at areas other than toys and faces, suggesting that infants were looking around the room to support locomotor exploration. Moreover, joint attention was most frequent (and most similar to rates from stationary tasks) when infants were sitting (and thus stationary) compared to prone and upright postures that might have involved locomotion (crawling and walking). Naturalistic studies of eye movements in children and adults show that the allocation of visual attention is tied to ongoing tasks and goals (Franchak & Adolph, 2010; Hayhoe & Ballard, 2005; Land & Hayhoe, 2001). When unconstrained in a novel playroom, infants' may have prioritized exploring the surrounding environment and thus spent less time engaged in stationary social play. The presence of an experimenter in the room, who was needed to ensure infants' safety, might also have captured some of infants' attention despite the experimenter's attempts to be unobtrusive. In future research, more fine-tuned analyses of infants' subtasks during play (e.g., exploring the room vs. stationary play) would provide more insight into how infants distribute visual attention in different contexts.

Conclusion

Taking a systems view, social interactions emerge through the coordination of two partners' behaviors. Most research has focused on how infants' developing language, cognitive, and social abilities influence social interactions. The current study suggests that infants' and caregivers' motor behavior should be considered part of that system. In everyday life, observers must weigh visual-motor trade-offs of multiple ongoing tasks to determine whether looking is worth the effort. Infants may not choose to look up at a caregiver's face when it means tilting their heads away from toys. Caregivers must decide whether it is worth sitting down to play when the infant might spring up and run across the room. Every movement infants and caregivers make has consequences for obtaining visual information. Studying naturalistic behavior brings us closer to understanding the structure and content of infants' opportunities for learning in everyday life. Future work can further inform theories of learning by measuring naturalistic behavior across a wider range of ages and in other naturalistic contexts.

Table 1. Inferential statistics for the four indices of social looking—face looking (by observer, infants looking at caregivers' faces vs. caregivers looking at infants' faces), mutual gaze (by the dyad), body looking (by observer, infants looking at caregivers' bodies vs. caregivers looking at infants' bodies), and joint attention (by the dyad)—according to infant and caregiver posture. Face and body looking were tested with observer (infant looking, caregiver looking) × posture ANOVAs. Effects of posture on joint attention and mutual gaze were tested with one-way ANOVAs. Separate tests were conducted for infant posture (prone vs. sitting vs. upright) and caregiver posture (down vs. up).

Measure	Posture	Posture main effect	Observer main effect	Posture × observer
Face looking	Infant	**$F(2,26) = 6.75$, $p = .004$, partial-$\eta^2 = .62$**	**$F(1, 13) = 151.23$, $p < .001$, partial-$\eta^2 = .92$**	$F(2,26) = 2.72$, $p = .084$, partial-$\eta^2 = .17$
Face looking	Caregiver	**$F(1, 11) = 19.78$, $p = .001$, partial-$\eta^2 = .62$**	**$F(1, 11) = 94.52$, $p < .001$, partial-$\eta^2 = .90$**	**$F(1, 11) = 11.22$, $p = .006$, partial-$\eta^2 = .51$**
Mutual gaze	Infant	**$F(2, 28) = 4.08$, $p = .028$, partial-$\eta^2 = .23$**	--	--
Mutual gaze	Caregiver	**$F(1, 11) = 38.63$, $p < .001$, partial-$\eta^2 = .78$**	--	--
Body looking	Infant	$F(2, 26) = 1.32$, $p = .284$, partial-$\eta^2 = .09$	**$F(1, 13) = 82.77$, $p < .001$, partial-$\eta^2 = .86$**	**$F(1, 13) = 6.02$, $p = .007$, partial-$\eta^2 = .316$**
Body looking	Caregiver	$F(1, 11) = 1.52$, $p = .244$, partial-$\eta^2 = .12$	**$F(1, 11) = 70.42$, $p < .001$, partial-$\eta^2 = .87$**	$F(1, 11) = 0.83$, $p = .381$, partial-$\eta^2 = .07$
Joint attention	Infant	**$F(2, 28) = 6.65$, $p = .004$, partial-$\eta^2 = .32$**	--	--
Joint attention	Caregiver	**$F(1, 11) = 13.24$, $p = .04$, partial-$\eta^2 = .55$**	--	--

*Significant results are shown in bold font.

Table 2A. Means and standard deviations (in parentheses) for the four indices of social looking—face looking (by observer, infants looking at caregivers' faces and caregivers looking at infants' faces), mutual gaze (by the dyad), body looking (by observer, infants looking at caregivers' bodies and caregivers looking at infants' bodies), and joint attention (by the dyad)—according to locomotor status (whether the infant was a crawler or walker).

Measure	Crawlers	Walkers
Infant face looking	4.0% (2.5)	4.8% (3.0)
Caregiver face looking	34.6% (8.3)	28.5% (9.7)
Mutual gaze (dyad)	2.7% (2.1)	2.3% (1.4)
Infant body looking	12.3% (7.1)	17.8% (9.9)
Caregiver body looking	40.5% (5.8)	41.6% (8.7)
Joint attention (dyad)	19.1% (17.1)	15.2% (10.1)

Table 2B. Inferential statistics for social looking indices— face looking (by observer, infants looking at caregivers' faces vs. caregivers looking at infants' faces), mutual gaze (by the dyad), body looking (by observer, infants looking at caregivers' bodies vs. caregivers looking at infants' bodies), and joint attention (by the dyad) —according to infant locomotor status. Face looking and body looking were tested in 2 observer (infant, caregiver) × by 2 infant locomotor status (crawler vs. walker) ANOVAs. Effects of locomotor status on mutual gaze and joint attention were tested in one-way ANOVAs.

Measure	Status main effect	Observer main effect	Status × observer
Face looking	$F(1,14) = 1.32$, p = .270, partial-η^2 = .086	**$F(1, 14) = 125.65$, $p < .001$, partial-η^2 = .90**	$F(1, 14) = 1.98$, $p = .182$, partial-η^2 = .12
Mutual gaze	$F(1, 14) = 0.25$, $p = .622$, partial-η^2 = .02	--	--
Body looking	$F(1, 14) = 1.11$, $p = .311$, partial-η^2 = .07	**$F(1, 14) = 113.31$, $p < .001$, partial-η^2 = .89**	$F(1, 14) = 0.81$, $p = .384$, partial-η^2 = .06
Joint attention	$F(1,14) = 0.30$, $p = .590$, partial-η^2 = .02	--	--

*Significant results are shown in bold font.

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Figure Captions

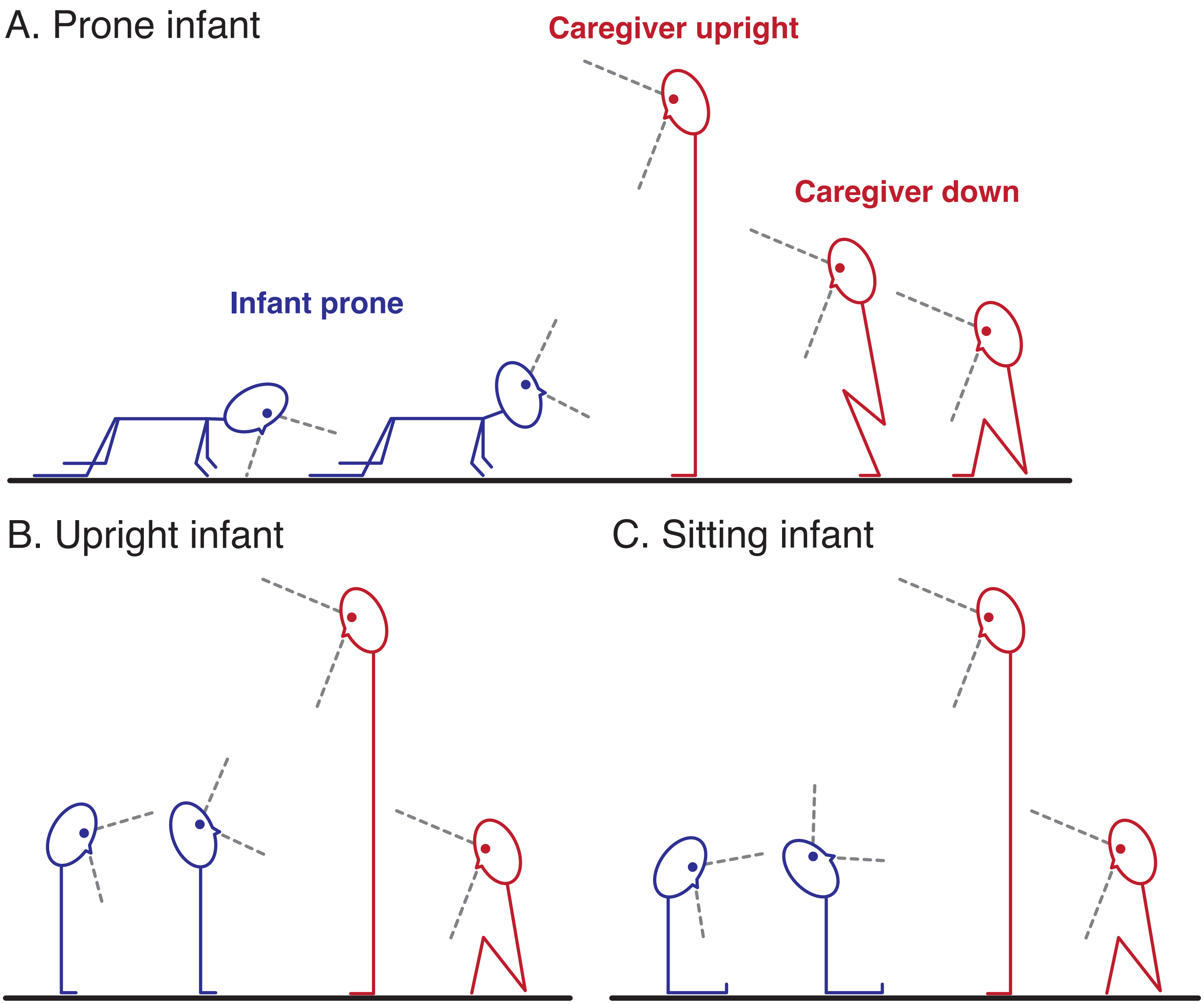
Figure 1. Schematic drawings of infant and caregiver field of view. Infants (blue) are displayed in (A) prone, (B), upright, and (C) sitting postures. Caregivers (red) are displayed in upright and down postures. Down includes both crouching and sitting as shown in (A). Infant head angles approximate the ranges reported by Kretch and colleagues (2014) for each posture. Caregiver head angles are fixed to a constant downward angle for the sake of illustration.

Figure 2. Simultaneous eye tracking of infant and caregiver. Third-person view (bottom panel) shows infant and caregiver playing while wearing head-mounted eye trackers. Eye trackers captured the first-person views of infant (top left) and caregiver (top right). White cross-hairs indicate each observer's point of gaze. White circles show the cursor (4º radius) used by coders to determine when infants and caregivers looked at toys and faces.

Figure 3. Face looking (A) and body looking (B) according to infant posture, and face looking (C) and body looking (D) according to caregiver posture. Data are collapsed across locomotor status. Error bars show 1 SE.

Figure 4. Percent of time that (A) infants and (B) caregiver spent in different postures. Data are divided according to infants' locomotor status. Error bars show 1 SE.

Figure 5. Percent of time that infants and caregivers looked at each others' faces compared to toys. Error bars show 1 SE.



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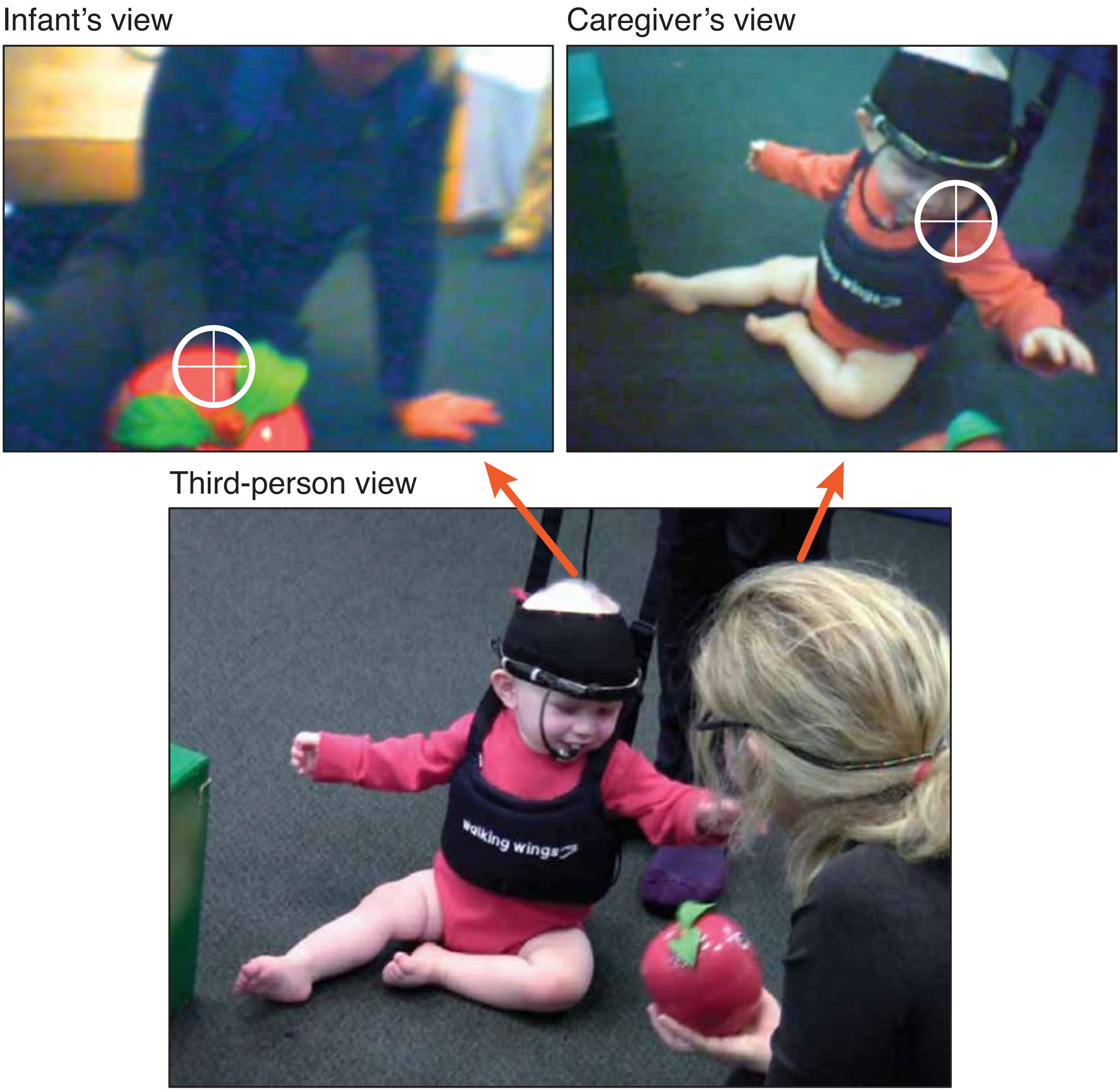

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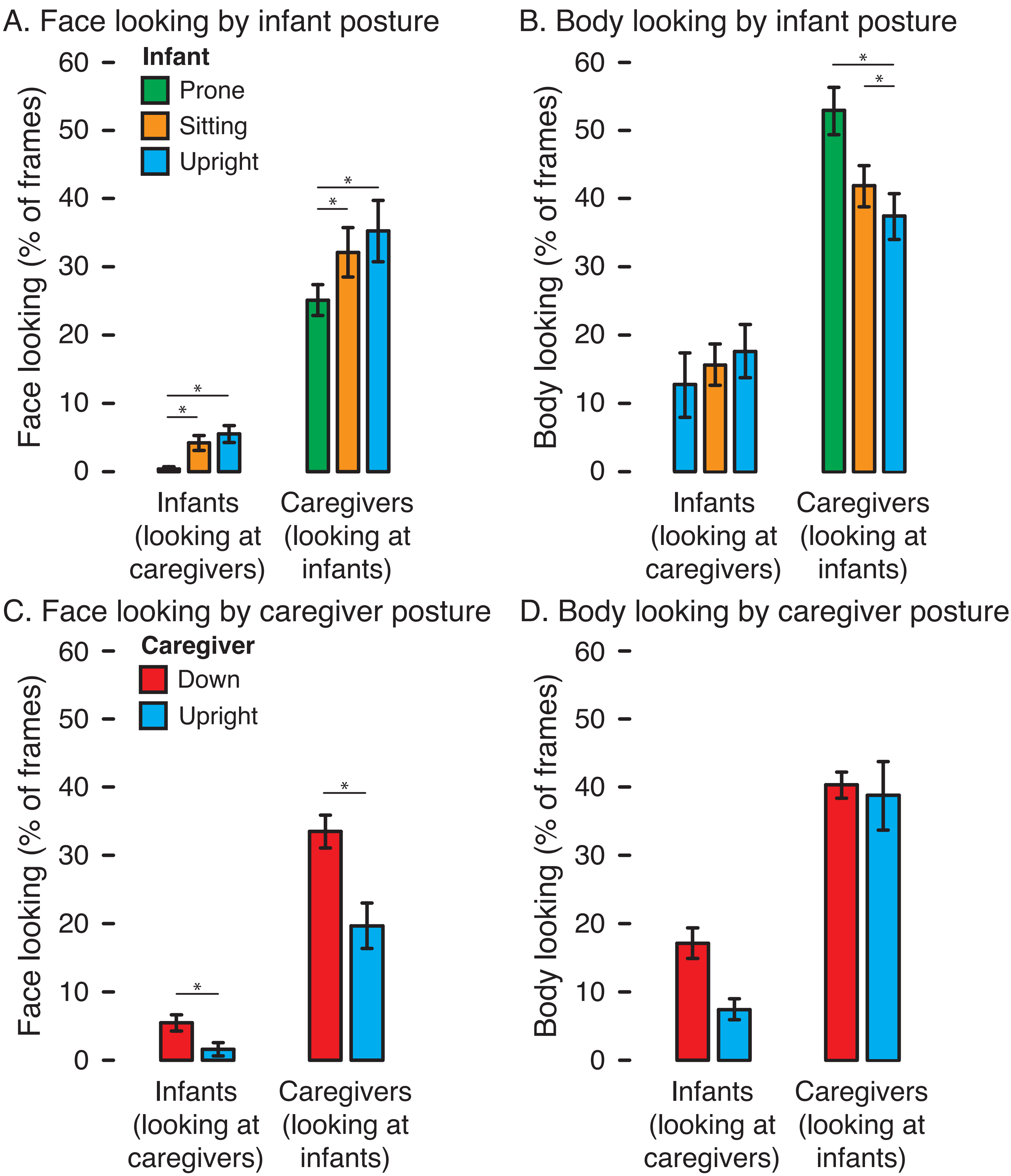

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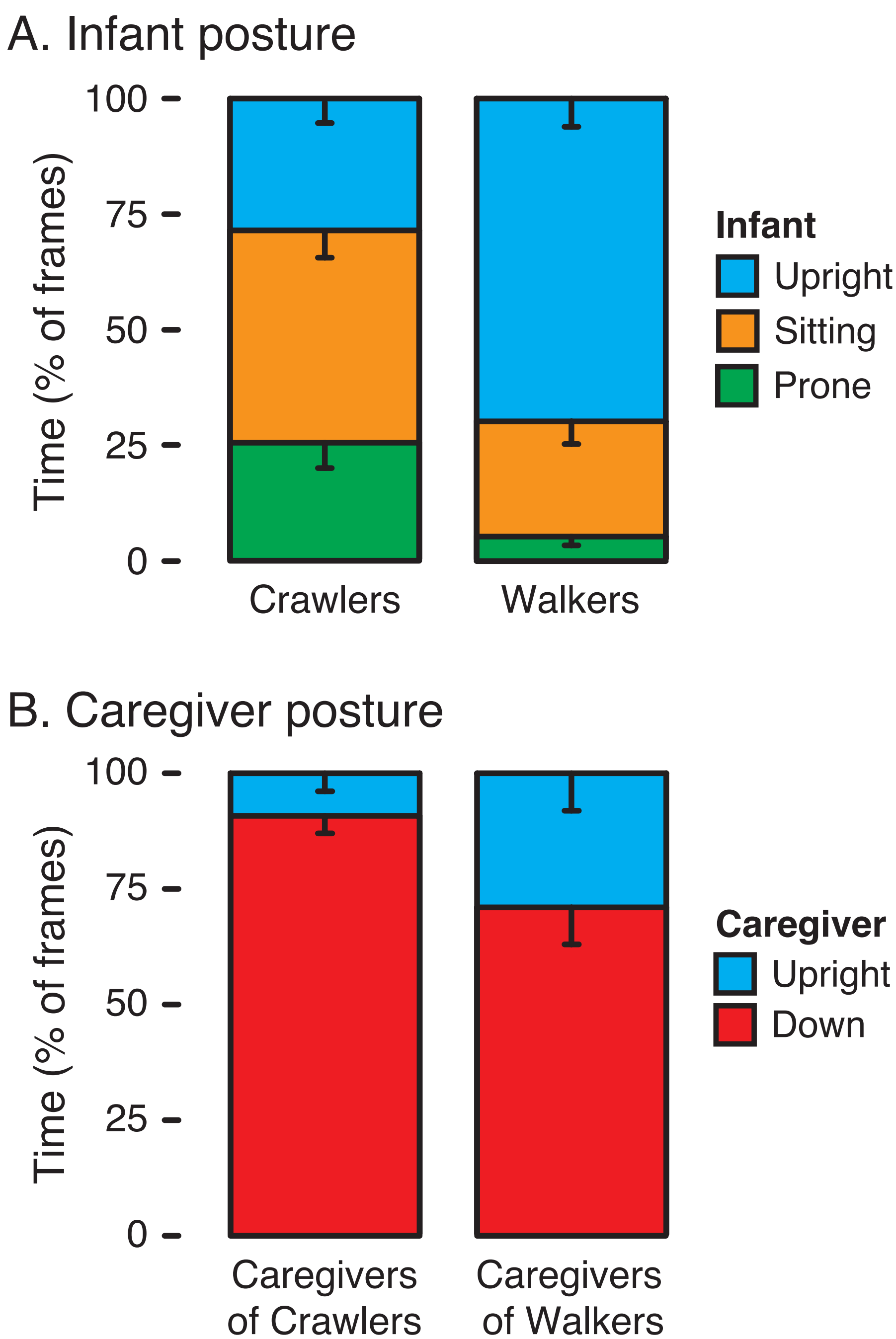

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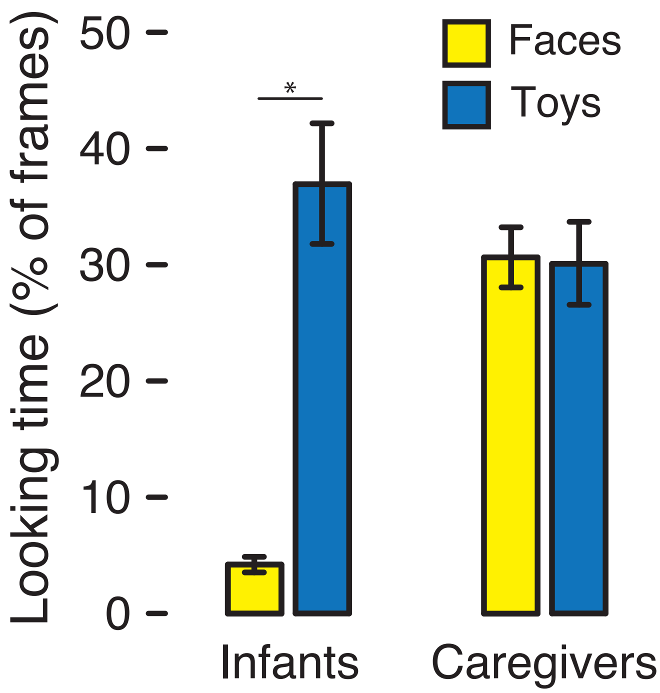

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