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Postural Position Constrains Multimodal Object Exploration in Infants

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Recent research has revealed the important role of multimodal object exploration in infants' cognitive and social development. Yet, the real-time effects of postural position on infants' object exploration have been largely ignored. In the current study, 5- to 7-month-old infants ($N = 29$) handled objects while placed in supported sitting, supine, and prone postures, and their spontaneous exploratory behaviors were observed. Infants produced more manual, oral, and visual exploration in sitting compared to lying supine and prone. Moreover, while sitting, infants more often coupled manual exploration with mouthing and visual examination. Infants' opportunities for learning from object exploration are embedded within a real-time postural context that constrains the quantity and quality of exploratory behavior.

Infants' acquisition of new action capabilities can facilitate a cascade of cognitive and social developments (Campos et al., 2000; Gibson, 1988; Piaget, 1954), which in turn, can drive new advances in infants' motor actions and exploration in an ever increasing spiral of development (Gibson, 1988). In particular, manual exploratory actions can generate new information for perceptual systems that subsequently facilitates advances in higher-level cognition. Dozens of recent studies have revealed developmental links between infants' acquisition of manual actions such as reaching and object manipulation and subsequent improvements in object individuation (Needham, 2000; Wilcox, Woods, Chapa, & McCurry, 2007)

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perceptual completion (Soska, Adolph, & Johnson, 2010), problem-solving (Lobo & Galloway, 2008), and social understanding (Sommerville, Woodward, & Needham, 2005). In these studies, infants were placed in a sitting position and researchers observed their natural exploratory skill (Baumgartner & Oakes, 2013; Eppler, 1995; Soska et al., 2010) or experimentally manipulated their hands-on experiences (Libertus & Needham, 2010; Lobo & Galloway, 2008; Sommerville, Hildebrand, & Crane, 2008). Performance in the "action" task was used to predict performance in the cognitive or social task. The conclusion from these studies is that infants' object exploration can be a driving force in cognitive and social development. Apparently, the ability to explore objects opens up new opportunities for learning.

Indeed, learning depends on the quantity and variety of object exploration (Baumgartner & Oakes, 2013; Eppler, 1995; Soska et al., 2010). Different exploratory actions generate different kinds of perceptual information (Bourgeois, Khawar, Neal, & Lockman, 2005; Lederman & Klatzky, 1987; Palmer, 1989; Rochat, 1989; Ruff, 1984). Fingering an object involves running the fingers along the edges and generates information about object shape and contour. Rotating an object reveals its sides and back and provides information about 3D structure. Transferring an object between hands gives information about object weight and form.

Yet, underlying object exploration is a critical but largely ignored contributor: posture. As Reed (1982, 1989) asserted, posture underlies all actions. Every action takes place in a postural position, whether sitting on mother's lap, lying supine in a crib, or sprawled prone on the floor. In each position, manual actions change the constraints on postural control by shifting the body's center of mass, such that infants must keep the trunk stable and balanced (Bertenthal & von Hofsten, 1998; Harbourne, Lobo, Karst, & Galloway, 2013). Without adequate postural control, exploratory actions, such as looking, touching, grasping, and so on, are compromised. The development of postural control generally starts in infants' necks and then moves down the trunk, emerging next in the upper back, then the lower back, and finally the hips (Cignetti, Kyvelidou, Harbourne, & Stergiou, 2011; Harbourne et al., 2013; Rachwani et al., 2013). As infants continuously gain greater control of descending muscle groups from head to hips, they are better able to keep the head balanced above the outstretched legs in sitting (Kyvelidou et al., 2009), to keep the head propped and chin tucked while lying prone, and to keep the head in midline while bringing the arms to midline while supine (Bly, 1994; Piper, Pinnell, Darrah, Maguire, & Byrne, 1992).

Increased control of posture in sitting helps infants to reach out and grasp objects and to subsequently explore them. Advances in reaching skill rely on improvements in neck, trunk, and hip control (van der Fits, Klip, van Eykern, & Hadders-Algra, 1999; Hopkins & Rönnqvist, 2002; Rachwani et al., 2013; Rochat & Goubet, 1995). Visually guiding the hand to a target requires a stable trunk to support fluid arm movement, and the neck, head, and eyes must work in concert with the trunk to facilitate eye gaze (Bertenthal & von Hofsten, 1998; de Graaf-Peters, Bakker, van Eykern, Otten, & Hadders-Algra, 2007; Thelen & Spencer, 1998). At first, infants rely on two-handed reaching to the front that is less taxing to postural control (White, Castle, & Held, 1964). After they gain control of the sitting posture, infants can use one-handed reaches to each side of the body (Rochat, 1992). Moreover, the ability to self-sit promotes coupling of eye and hand movements to allow coordinated visual–manual exploration (Soska et al., 2010). Bolstering postural control in a sitting position during object exploration improves infants' attention to novel object properties (Woods & Wilcox, 2013); similarly, scaffolding posture in a sitting position facilitates object attention and exploration in children with cerebral palsy (Saavedra, Woollacott, & van Donkelaar, 2010). Thus, postural development can facilitate new, richer ways of exploring objects, which subsequently can guide cognitive and social learning and further hone exploration.

But before infants can sit independently, they have the opportunity to explore objects in other postures: supine on their backs or prone on their bellies. Moreover, following pediatricians' advice to give infants "tummy time," caregivers place infants for extended time in a prone posture playing with toys (Chizawsky & Scott-Findlay, 2005). Why then is the development of postural control in a sitting posture such an important setting event for infants' manual actions and cognitive development? A likely possibility is that the sitting position poses fewer constraints on object exploration than do supine and prone postures. However, we know little about the real-time effects of postural position on infants' manual actions (Thelen & Spencer, 1998)—that is, how exploration of an object in hand changes as infants shift between sitting, supine, and prone postures. By 3 months of age, infants bring the hand to the mouth less often while prone compared to supine (Rocha & Tudella, 2008). Savelsbergh and colleagues (Carvalho, Tudella, & Savelsbergh, 2007; Out, van Soest, Savelsbergh, & Hopkins, 1998) showed that in a supine posture, infants display less mature reaching patterns because of the added constraint of fighting against gravity to lift and control the hand and arm. Their reaches are more jerky and spastic. Moreover, in supine compared to upright sitting, infants show less organized reaching and more whole body movements—spontaneously wriggling and writhing as their hands surge forward to handle objects (van der Fits et al., 1999; Soska, Galeon, & Adolph, 2012).

While infants are gaining new postural control in their hips and backs for upright sitting and honing neck and trunk control in supine and prone positions, they are also finding new ways to engage with objects. Younger infants rely largely on oral exploration (putting the toy in the mouth); older infants rely more on visual examination (Rochat, 1989; Ruff, 1986) or alternating between mouthing and looking, potentially mapping tactile information from oral exploration to objects' visual properties (Ruff, Saltarelli, Capozzoli, & Dubiner, 1992). Infants also begin to couple exploratory actions by coordinating looking, mouthing, and manipulating (Ruff, 1989). Multimodal object exploration is tremendously important for facilitating developments in cognition and perception; it can be the strongest predictor of infants' learning (Bahrick, Lickliter, & Flom, 2004; Baumgartner & Oakes, 2013; Ruff, 1989; Soska et al., 2010).

CURRENT STUDY

The current study sought to examine how real-time changes in infants' postural position affect the frequency of exploratory actions—manual, oral, and visual exploration and their coordinated interactions. Research investigating the developmental effects of age and postural skills on object exploration has grown steadily over the past two decades (e.g., Hopkins & Rönnqvist, 2002; Lobo & Galloway, 2008; Rochat & Goubet, 1995; Soska et al., 2010; Woods & Wilcox, 2013). But how real-time changes in postural position—the shifts in position between supine, prone, and sitting—affect exploratory behavior, over and above developmental changes in postural control, has remained largely unstudied.

Dramatic changes in manual exploration and postural development emerge at around 5–7 months of age (Bly, 1994). Thus, we observed infants in this age range to investigate how posture affects object exploration. To replicate an exploratory environment familiar to infants, we observed them playing with toys while on a carpeted floor. The three postures we chose were also common and familiar to infants: sitting upright held by a caregiver, lying supine on their backs, and lying prone on their bellies.

Most important, each of these postures is likely to constrain or promote exploration in different ways. To explore objects in a prone posture, infants need to prop their chest off the ground using either an elbow or one hand to support the upper body while the other hand explores the toy. While the toy may always be positioned right in front of infants' line of sight, coordinating hand movements with eye gaze requires continual head-raising, which some infants find exhausting or aversive (Kadey &

Roane, 2012). We expected that manual exploration that challenges this upper body control—especially bimanual actions and actions involving full arm movements, such as rotating or bringing toys to and from the mouth—would be less frequent while prone.

Exploring objects in a supine posture involves a different set of challenges. Infants need to generate high amounts of torque to initiate and alter reaching movements (Carvalho et al., 2007; Fallang, Saugstad, & Hadders-Algra, 2000; Lobo & Galloway, 2008). Holding the hands aloft shifts the body's center of mass outward and upward, taxing motor coordination, and destabilizing the arm (Out et al., 1998). Although both hands might be free for exploration, unlike prone, infants must continually fight against gravity to keep their arms raised while manipulating objects and simultaneously keeping them in view. Moreover, even with the head resting on the ground, infants face more challenges for head control while supine compared to when tilted upright, including recruiting additional activation of neck muscles and managing more degrees of freedom for movement (de Lima-Alvarez, Tudella, van der Kamp, & Savelsbergh, 2013). Thus, manual actions and coupled head movements should be more difficult and occur less frequently—especially actions such as looking while manipulating, which requires both arm and neck control.

Self-sitting relies on a bevy of control mechanisms in early development; keeping balance while sitting involves coordinated use of muscles in the neck, trunk, hips, and even legs (Harbourne, Giuliani, & Neela, 1993; Rachwani et al., 2013). To supplement young infants' poor balance control, caregivers may prop infants against pillows or furniture, purchase commercial supportive devices, or hold infants in a sitting position. Infants sometimes place their hands between their outstretched legs to aid balance in a sitting posture, performing a "tripod sit," but this occupies their hands (Harbourne et al., 2013; Soska et al., 2010). Once infants' hands are freed from supporting functions (through self-sitting or parental intervention), exploration should be easiest. Objects can be held off of the ground and close to infants' center of mass (Cignetti et al., 2011; Thelen & Spencer, 1998). Infants only need to keep their hands suspended slightly above the ground, requiring less torque generation during whole arm movements and promoting better control than when lying supine (Carvalho, Tudella, Caljouw, & Savelsbergh, 2008; Carvalho et al., 2007; Out et al., 1998). Head control is easier in upright sitting positions (Hopkins & Rönnqvist, 2002; de Lima-Alvarez et al., 2013), and the eyes can rest downward. Experience sitting upright leads to better coordination of the head, eyes, and hands (Bertenthal & von Hofsten, 1998; Soska et al., 2010). In the current study, to equalize control requirements across the infants—and because we were primarily interested in the real-time effects of posture—parents held all of the infants while sitting. Nevertheless, developmental factors such as infants' age and postural experiences also affect object exploration, so we statistically controlled for these time-varying factors in our analyses.

METHOD

Participants

We tested 29 infants (14 boys and 15 girls) ranging from 4.70 to 7.43 months of age (M = 6.02). All were healthy and born at term. Families were recruited from a commercial database and through visits to nearby hospitals. Most families were middle class and white. Data from an additional 14 infants were collected but excluded because of fussiness (three infants while prone, three infants while supine, one infant while sitting, and four infants in all three postures), experimenter error (two infants), and video equipment failure (one infant). Infants received a small toy or t-shirt as a souvenir for participation.

In a structured interview (see Adolph, 2002)—using baby books and calendars to augment their memories—parents reported the first day their child could roll between supine and prone (without stopping on the side), prop their chest off the ground in a prone position (for 30 sec using two hands), tripod sit (for 30 sec with the hands placed between the outstretched legs), and self-sit independently (for 30 sec without using the hands, legs outstretched in front of the body). Parents expressed difficulty in recalling the onset of rolling and prone prop; eight parents said they were too unsure to provide an onset date for rolling, and two different parents could not provide an onset date for prone prop. We calculated postural experience as the number of days between onset and test dates. For the infants of parents who did provide onset dates, rolling experience averaged 51.19 days (SD = 34.02) and prone prop experience averaged 63.33 days (SD = 37.45). However, age at testing did not reliably correlate with days of rolling experience, $r(19) = .29$, $p > .1$ or prone prop experience, $r(25) = .25$, $p > .1$. Thus, we doubted the validity of parents' reports for these two measures and did not include them in subsequent analyses.

All parents reported their infant's sitting experience. Fourteen infants could not sit independently, four infants were able to tripod sit only, and 11 infants could self-sit without using the hands for support. An experimenter verified parent report of infants' sitting abilities in the laboratory. Experience with tripod sitting averaged 10.00 days (SD = 14.13) and self-sitting averaged 13.35 days (SD = 19.27). Both measures of sitting experience correlated with each other, $r(27) = .50$, $p = .006$, and with age at testing, $r(27) = .38$, $p = .04$ for tripod sitting; $r(27) = .59$, $p = .001$ for self-sitting.

We also asked parents to rate how frequently their child had played with toys while in prone, supine, and supported sitting postures in the past 2 weeks—responding “never,” “seldom,” “sometimes,” or “often” for each position. Table 1 shows the frequency of play in each posture by number of infants. No parent reported that their child never played with toys in any posture or seldom played in more than one posture. All parents reported their infants played often in at least one posture. Frequency of play in each posture did not reliably differ by sitting ability, χ^2s(2) < 4.2, *p*s > .1.

Materials and procedure

To elicit a variety of exploratory behaviors, we constructed 12 toys (Figure 1) made of different materials—four of solid wood, four of hollow plastic, and four of squishy foam. The toys had colorful patterns on their fronts and backs, were 7–10 cm in length, and could be easily held by infants. The experimenter offered a different toy on each trial, and trials

TABLE 1
Number of Infants Playing in Each Posture in the Last 2 weeks by Frequency

	Never	*Seldom*	*Sometimes*	*Often*
Prone	0	8	10	11
Supine	0	3	8	18
Sitting	0	4	8	17

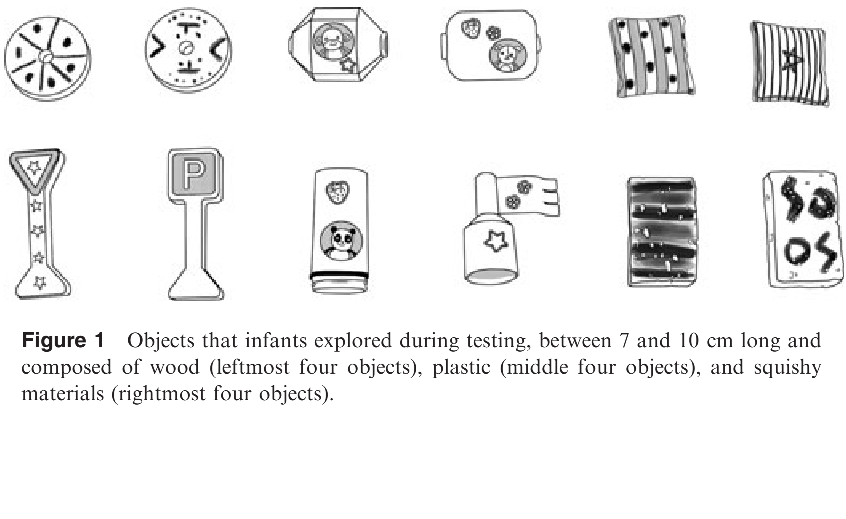

Figure 1 Objects that infants explored during testing, between 7 and 10 cm long and composed of wood (leftmost four objects), plastic (middle four objects), and squishy materials (rightmost four objects).

lasted until infants accumulated 60 sec of manual contact with the toy. At the beginning of each trial, the experimenter presented the toy at the center of the infant's chest. If the infant did not grasp the toy within 5 sec, the experimenter placed the infant's hands around the toy (34 of the 348 trials in the dataset). If the infant mishandled and dropped a toy and did not retrieve it within 5 sec (or it fell out of reach), the experimenter placed the toy back into the infant's hands (248 of the 348 trials). After 60 sec of accumulated manual contact, the experimenter collected the toy. After two trials were completed in the given posture, the experimenter placed the infant into the next posture. This pattern was repeated twice to arrive at 12 trials (four in prone, four in supine, four in sitting). Posture and toy order were counterbalanced independently, such that no particular toy was consistently paired with a particular postural condition across the sample.

Because some infants could not sit, all parents supported their infants in the sitting posture by holding them around the waist. In all postures, the infants faced away from their caregiver and the experimenter. A video camera recorded infants' posture, faces, and hands from a front-on view.

Data coding

A primary coder scored infants' manual, visual, and oral exploration of objects using Datavyu (www.datavyu.org), a computerized video coding software. The software allowed the coder to record the onset and offset of each exploratory action in a spreadsheet linked to the video for each session.

A primary coder scored every instance of three types of manual exploration (Ruff, 1989): *fingering* objects by running one or more fingers along the surface, *rotating* objects by turning an object more than 90° to expose its back side, and *transferring* objects between hands with no concurrent mouthing or touching of the upper body or legs. We had no a priori assumptions about the duration of each exploratory behavior and whether infants' actions would be organized into discrete, repetitive bouts. So, every sequential repetition of an action was scored as a unique event and its onset and offset were recorded. Thus, running a finger down and then up an object would count as two fingerings; turning an object over and then back again would count as two rotations, and moving an object from one hand into the other and back again would count as two transfers. The probability of one type of manual exploration overlapping another (e.g., fingering while rotating) was rare (<0.05% of all manual actions). Thus, we treated manual actions as mutually exclusive. In the few cases of temporal overlap, both actions were scored to preserve the total frequency, but the earlier-occurring action was coded as ending when the next manual action began.

Oral exploration was coded when infants brought an object into the mouth for 0.5 sec or more. The coder recorded the onset and offset of every *mouthing* event that met the 0.5 sec criterion. Fingering and rotating could co-occur with mouthing (but by definition, transferring could not) and were scored as the intersection of the manual and oral codes in the spreadsheet. For instance, infants could hold the toy in the mouth with one hand and finger the toy with their other hand.

Visual exploration was coded when infants looked at objects for 0.5 sec or more, and the onset and offset of *looking* that met the 0.5 sec criterion were recorded. Each type of manual exploration could co-occur with visual exploration and was scored as the overlap of the manual and visual codes. Visual and oral exploration could not co-occur (the toys were small and thus out of infants' field of view), but infants could *alternate* between mouthing and looking as a separate exploratory behavior (Ruff et al., 1992). Based on the coded onset and offset of oral and visual exploration, alternating was scored for each immediate switch (with 0 sec delay) from mouthing to looking or from looking to mouthing.

To determine inter-rater reliability of the codes, a second coder scored 33.3% of each infant's data. Coders agreed 92.1% of the time on the occurrence of manual exploration and its type ($\kappa = .90$), and they agreed 94.8% on the occurrence of oral and visual exploration ($\kappa = .94$). Correlations between primary and secondary coders for the durations of manual, oral, and visual exploration ranged from $r = .93$ to .96.

Data quantification

As a first step to quantifying infants' object exploration, we sampled and visualized small segments of infants' data for sequential exploratory data analysis (Sanderson et al., 1994). Figure 2 shows an exemplar timeline of one infant's object exploration during a 30-sec epoch taken from the middle of a supported sitting trial. These data are representative of infants' exploratory patterns across the sample. Action modalities frequently overlapped (e.g., fingering and mouthing), and the infants frequently switched among exploratory actions (e.g., rotating, fingering, rotating, transferring). Infants seldom performed a single action repeatedly. Looking happened over long swathes of time—sometimes co-occurring with manual actions—punctuated by looks away (around the room or at a part of their body) or alternated with mouthing.

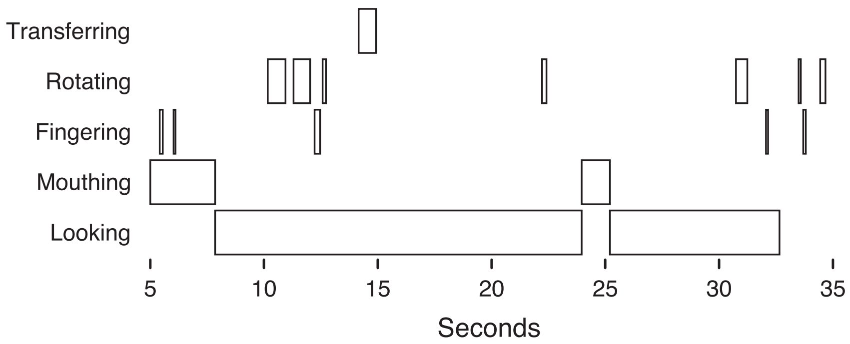

Figure 2 Exemplar timeline of exploratory actions from a single infant during the middle 30 sec of a trial. Each bar depicts the duration of a discrete exploratory action.

Examining the manual actions, we noticed that most were short in duration. Fingering ranged from 0.2 to 1.9 sec (87% of fingerings were under 1 sec), rotating ranged from 0.2 to 5.0 sec (90% of rotations were under 1.5 sec), and transferring ranged from 0.3 to 4.0 sec (94% of transfers were under 2.0 sec). Over 70% of all manual actions were under 1 sec. Thus, we decided that the most informative way to quantify fingering, rotating, and transferring was the frequency of the behavior (rather than duration). Alternating mouthing and looking, as it was a punctate event by definition, was quantified by frequency. The durations of oral and visual exploration, however, varied widely across infants and trials—from 0.5 to 50.2 sec for mouthing and from 0.5 to 49.7 sec for looking. So, we quantified oral and visual exploration in terms of duration rather than frequency. We quantified the co-occurrence of manual exploration with oral or visual exploration based on the frequency of the manual action, as the overlap of the manual and oral or visual codes was usually brief.

For analyses, we summed across all of the trials within a posture condition: the frequencies of each type of manual exploration (fingering, rotating, transferring, and alternating), the durations of visual and of oral exploration, and the frequencies of each type of multimodal exploration. The frequencies and durations of all of the exploratory actions and their co-occurrences were approximately normally distributed and thus met criteria for analyses of variance. Preliminary analyses indicated that infants' sex, trial number, and the presentation order of posture conditions did not affect object exploration. There were also no reliable differences in infants' exploration related to toy material, toy shape, or presentation order of the toys.

RESULTS

Overall, some types of exploration were more prevalent than others, although every infant produced each exploratory behavior at least once. As shown by the height of the bar clusters in Figure 3, infants fingered and rotated objects more frequently than they transferred objects, and they spent longer durations looking at objects than mouthing them. On most trials, infants fingered and rotated objects multiple times, but they transferred objects less than once per trial. Infants alternated mouthing and looking once or twice per trial and spent about a quarter of each trial mouthing objects and half of each trial looking at them. Overall, coupled oral–manual exploration was less prevalent than manipulating without mouthing (Figure 4), but coupled visual–manual exploration occurred about as frequently as manipulating the object without looking at it (Figure 5).

Effects of age, postural experience, and frequency of play

Next, we explored the effects of infants' age at testing, self-sitting experience, and tripod sitting experience on manual, oral, and visual exploration. The goal was to understand how these time-varying factors affected infants' exploratory activity and to account for them when investigating posture condition effects. We also asked whether age and tripod and

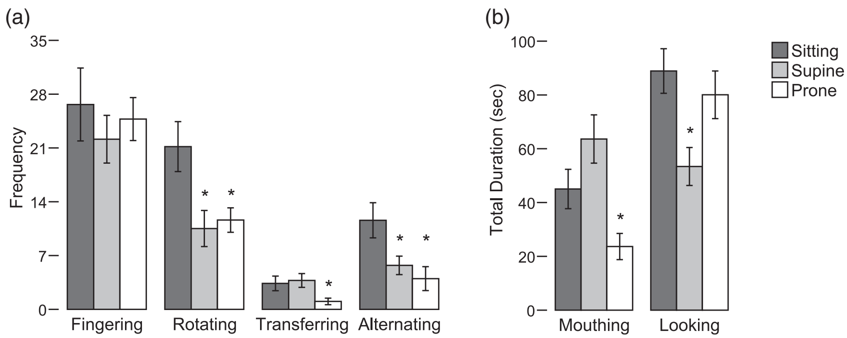

Figure 3 Infants' manual, oral, and visual exploration while in sitting, supine, and prone posture conditions. (a) The mean frequency of fingering, rotating, transferring, and alternating between mouthing and looking summed across all trials in each posture. (b) The mean duration of mouthing and looking totaled across all trials in each posture. Stars represent postures where the frequency of exploration was significantly lower ($p < .05$) compared to other postures. Bars represent standard errors.

self-sitting experiences affected object exploration differently in each postural position. Because age and both measures of sitting experience were highly intercorrelated, we used multivariate linear regression to examine the unique contribution of each factor on infants' exploratory behavior, controlling for the effects of the other predictors. Each measure was centered on its mean across the sample. We also included the interaction between age and self-sitting experience as a model term: It explained additional variance and improved model fit (M adjusted $R^2 = .15$, range = .01–.32).

The regression analysis revealed a marginal main effect of testing age, Pillai's trace = .35, $F(4, 21) = 2.79$, $p = .053$; frequency of rotating increased with infants' increasing age, $\beta = .61$, $SE = .27$, $F(1, 24) = 4.90$, $p = .037$. There was a main effect of independent sitting experience, Pillai's trace = .41, $F(4, 21) = 3.69$, $p = .02$; transferring increased with more days of self-sitting experience, $\beta = .46$, $SE = .15$, $F(1, 24) = 9.08$, $p = .006$. But self-sitting experience also interacted with testing age, Pillai's trace = .38, $F(4, 17) = 2.90$, $p = .03$, such that nonsitters displayed marginally more transfers with increasing age, $\beta = .13$, $SE = .07$, $t = 1.85$, $p = .084$, but self-sitters did not, $t = .06$, $p > .1$. There were no effects of age or self-sitting experience on fingering, alternating, looking, or mouthing, all Fs < 4, ps > .1; tripod sitting experience had no reliable influences on object exploration, Pillai's trace = .17, $F(4, 21) = 1.09$, $p > .1$. Moreover, the effects of age and both types of sitting experience did not reliably differ with postural position, all Pillai's trace < .22, Fs < 1.4, ps > .1.

Finally, we found no reliable differences in manual, oral, or visual exploration overall or in any posture condition based on parents' reports of infants' frequency of play ("seldom," "sometimes," "often") in each position in the last 2 weeks (all Pillai's trace < .75, ps > .1). (We obtained identical results when frequency of play was considered as "often" or "not often.")

Subsequent analyses examined the effects of infants' real-time postural position on the frequency of manual exploration and the duration of oral and visual exploration. We also asked how posture condition affected the occurrence of coupled oral–manual exploration and coordinated visual–manual exploration. Age at test and self-sitting experience were included as covariates in the analyses to control for their influences when assessing the effects of postural position. Follow-up comparisons were evaluated at the mean values of the covariates and compared against Sidak-corrected alpha levels to minimize experiment-wise error rate (Abdi, 2007). Sphericity could not be assumed for the fingering and alternating data, so F tests on these measures were Greenhouse–Geisser corrected.

Posture affects object exploration

Manual exploration

The frequency of manual exploration differed by posture condition (shown by the height of the bars within each cluster in Figure 3a). Fingering was the most frequent exploratory action ($M = 26.65$ in sitting, $SD = 25.53$; $M = 22.14$ in supine, $SD = 16.74$; $M = 24.76$ in prone, $SD = 15.05$) and did not differ across postures. Infants rotated objects more frequently while sitting ($M = 21.17$, $SD = 17.50$) compared to supine ($M = 10.52$, $SD = 12.64$) and prone postures ($M = 11.62$, $SD = 8.57$). Infants transferred objects from hand to hand more often in sitting ($M = 3.38$, $SD = 5.12$) and supine ($M = 3.76$, $SD = 4.84$) than in prone ($M = 1.03$, $SD = 2.28$). Alternating between mouthing and looking was more frequent in sitting ($M = 11.59$, $SD = 12.31$) than in supine ($M = 5.72$, $SD = 6.47$) and in prone ($M = 4.00$, $SD = 8.39$).

A one-way multivariate analyses of covariance (MANCOVA), with posture condition (sitting, supine, prone) as a within-participant factor, age and self-sitting experience as covariates, and frequency of fingering, rotating, transferring, and alternating as dependent measures, confirmed a significant effect of posture, Pillai's trace = .57, $F(8, 19) = 3.21$, $p = .018$. Follow-up univariate analyses of covariance (ANCOVA) for each type of manual exploration affirmed no effect of posture condition on fingering, $F(1.61, 41.75) = 0.47$, $p > .1$. The ANCOVA revealed a significant effect of posture on rotating, $F(2, 52) = 7.57$, $p = .001$, partial $\eta^2 = .23$. Pairwise comparisons confirmed more frequent rotating in sitting compared to both supine ($p = .002$) and prone ($p = .007$) and similar frequencies between supine and prone ($p > .1$). There was also a reliable posture effect on transferring, $F(2, 52) = 4.78$, $p = .012$, partial $\eta^2 = .16$. Infants performed more transferring while supine compared to prone ($p = .005$), marginally more transferring while sitting compared to prone ($p = .03$), and comparable frequencies between sitting and supine ($p > .1$). Finally, the ANCOVA also showed a significant posture effect on alternating, $F(1.26, 32.78) = 7.26$, $p = .002$, partial $\eta^2 = .22$; alternating was more frequent while sitting compared to while supine ($p = .019$) and while prone ($p = .006$) but similar between supine and prone ($p > .1$).

Oral exploration

Mouthing also varied systematically across the three posture conditions (Figure 3b, left side). Infants explored objects orally for the longest total duration while supine ($M = 63.62$ sec, $SD = 48.34$), the next longest while sitting (*M* = 45.04 sec, *SD* = 39.39), and for the shortest total duration while prone (*M* = 23.64 sec, *SD* = 26.20). A one-way ANCOVA, with posture condition as a within-participant factor and testing age and self-sitting experience as covariates, confirmed an effect of posture on oral exploration, $F(2, 52) = 11.80$, $p < .001$, partial $\eta^2 = .31$. Follow-up comparisons revealed longer total mouthing while sitting compared to prone ($p = .017$) and supine compared to prone ($p < .001$) and similar mouthing durations between sitting and supine ($p > .1$).

Visual exploration

Looking duration changed across postures as well (Figure 3b, right side) and showed a contrasting pattern to oral exploration. Visual exploration was equally long in sitting (*M* = 88.90 sec, *SD* = 44.59) and prone postures (*M* = 80.05 sec, *SD* = 47.72), but looking at objects was shortest when infants were supine (*M* = 53.40 sec, *SD* = 38.00). A one-way ANCOVA on visual exploration, with posture condition as a within-participant factor and age and self-sitting experience as covariates, confirmed a reliable posture condition effect, $F(2, 52) = 7.34$, $p = .002$, partial $\eta^2 = .22$. Pairwise comparisons affirmed longer total looking while infants were sitting ($p < .001$) and prone ($p = .002$) compared to supine and similar looking durations between sitting and prone ($p > .1$).

Posture affects multimodal object exploration

Oral–manual exploration

Concurrent oral–manual exploration was relatively rare in every posture, but infants were more likely to display concurrent oral–manual exploration—mouthing objects while exploring them with their hands—in the sitting condition. For fingering (Figure 4a), posture condition altered the relative frequency of exploration with concurrent mouthing—fingering while mouthing was least frequent while prone. For rotating (Figure 4b), more exploration occurred during sitting compared to the other postures, but these additional rotations took place without concurrent mouthing.

A two-way MANCOVA on fingering and rotating, with posture (sitting, supine, prone) and oral exploration (with mouthing, no mouthing) as within-participant factors and testing age and self-sitting experience as covariates, revealed a main effect of oral exploration, Pillai's trace = .7, $F(2, 25) = 47.60$, $p < .001$. During both fingering and rotating, infants spent more time not mouthing the objects than mouthing them, $F\text{s}(1, 26) > 66$, $p\text{s} < .001$, partial $\eta^2\text{s} > .72$.

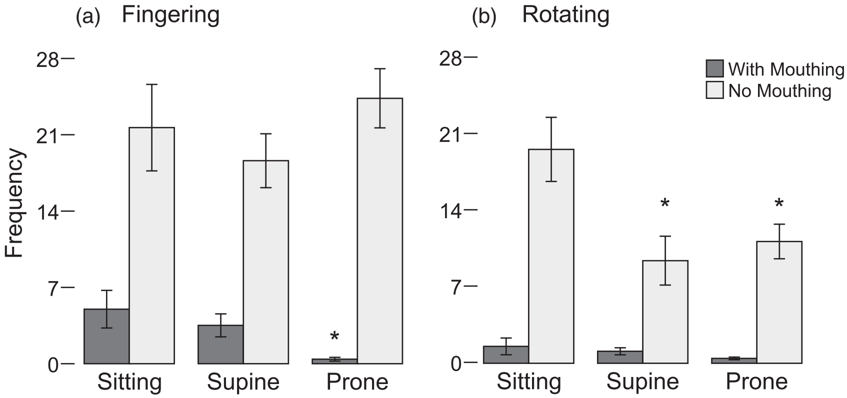

Figure 4 Coupled oral and manual exploration while infants were in sitting, supine, and prone postures. Mean frequency summed across trials for (a) fingering with mouthing and no mouthing and (b) rotating with mouthing and no mouthing. Stars indicate actions (fingering with mouthing, rotating with no mouthing) significantly lower than other postures ($p < .05$). Bars represent standard errors of the mean.

There was also a significant posture × oral exploration interaction, Pillai's trace = .53, $F(4, 23) = 6.41$, $p = .001$. Follow-up, two-way univariate analyses affirmed posture × oral exploration interactions for fingering, $F(1.82, 47.31) = 3.32$, $p = .049$, partial $\eta^2 = .11$, and for rotating, $F(2, 52) = 7.17$, $p = .002$, partial $\eta^2 = .21$. Pairwise comparisons revealed more concurrent mouthing and fingering in sitting compared to prone ($p = .014$) and supine compared to prone ($p = .005$) and similar frequencies between sitting and supine ($p > .1$). In contrast, there were no differences in the rate of fingering without mouthing between the three postures (*p*s > .1). The frequency of rotating concurrent with oral exploration was unaffected by posture (*p*s > .1). Rotating without mouthing was more frequent in sitting compared to supine ($p = .001$) and prone ($p = .011$) but similar between supine and prone ($p > .1$). In summary, concurrent manual–oral exploration was most frequent in sitting and supine postures, but only for fingering.

Visual–manual exploration

Figure 5 illustrates that the frequency of coupled visual–manual exploration differed by posture for fingering and transferring. While sitting, infants manually explored objects while looking as often or more often than while not looking. In the supine and prone posture conditions, they explored objects more often while not looking.

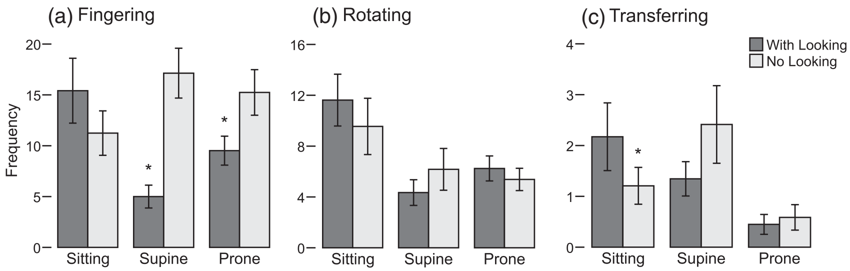

Figure 5 Manual exploration with looking and no looking while infants were in sitting, supine, and prone postures. Mean frequency summed across trials for (a) fingering, (b) rotating, and (c) transferring. Stars indicate actions where manipulating with looking and without looking were significantly different ($p < .05$) within a posture. Bars represent standard errors of the mean.

A two-way MANCOVA with posture condition (sitting, supine, prone) and visual exploration (with looking, no looking) as within-participant factors and age and self-sitting experience as covariates on fingering, rotating, and transferring revealed a main effect for visual exploration, Pillai's trace = .33, $F(3, 24) = 3.87$, $p = .02$. Follow-up univariate tests showed that, overall, fingering occurred more often while not looking than with looking, $F(1, 26) = 7.97$, $p = .009$, but rotating and transferring were equally frequent with and without looking, Fs $< .1$, ps $> .1$.

However, the MANCOVA also revealed a significant interaction between posture and visual exploration, Pillai's trace = .67, $F(6, 31) = 7.03$, $p < .001$. Follow-up univariate analyses confirmed reliable posture × visual exploration interactions for fingering, $F(1.57, 40.61) = 14.15$, $p < .001$, partial $\eta^2 = .35$, and transferring, $F(2, 52) = 3.29$, $p = .04$, partial $\eta^2 = .11$, but not for rotating, $F(2, 52) = 1.43$, $p > .1$. Fingering was more frequent without looking than with looking while supine ($p < .001$) and while prone ($p = .03$). In contrast, fingering was equally frequent with and without looking while sitting ($p > .1$). For transferring, in the sitting posture, infants explored while looking more often than not ($p = .03$); while supine and prone, they displayed transferring with and without looking equally (ps $> .1$). To recap, only in sitting did infants display more coupled (rather than decoupled) visual–manual exploration.

DISCUSSION

Recent research has taken seriously the idea posed most notably by Piaget (1954) and Gibson (1988)—that infants' manual actions can instigate learning about the physical and social world (Baumgartner & Oakes, 2013; Libertus & Needham, 2010; Sommerville et al., 2005; Soska et al., 2010; Wilcox et al., 2007). Largely ignored, however, is the real-time postural context in which object exploration unfolds—specifically, whether infants' postural positions constrain the frequency and duration of exploratory behavior. In the present study, we experimentally manipulated infants' posture position, as they explored objects while prone on their bellies, supine on their backs, and sitting upright supported by a caregiver. In a sitting posture, infants engaged in as much or more manual, visual, and oral exploration of objects as they did in prone and supine postures. Moreover, while sitting, infants were more likely to explore objects multimodally—coordinating manual exploration with oral and visual exploration.

Posture affects real-time exploration

What were the causes of infants' limited object exploration in the prone and supine positions? Familiarity with prone and supine postures is not likely to be an important factor. Every infant had experience playing with toys in each posture in the 2 weeks prior to testing. Older infants and those with more self-sitting experience showed higher frequencies of rotating and transferring, respectively, but these developmental effects did not vary across postural position and were controlled for in the analyses. Instead, constraints on exploration likely stemmed from the biomechanical and gravitational forces affecting infants in those postures.

Prone

In a prone posture on the floor, infants need to use one hand or arm to keep the chest aloft while the other hand and arm explore objects (Rocha & Tudella, 2008). Thus, as we predicted, actions involving two hands—like transferring—and actions involving full arm movements—rotating, alternating mouthing and looking—were hampered and occurred least frequently. Because oral exploration was difficult while prone, infants also explored objects with coordinated oral–manual exploration less often (especially while fingering). Placing an object in front of infants promotes head-raising and visual attention (Kadey & Roane, 2012; Rocha & Tudella, 2008); accordingly, looking while prone was comparable to sitting. Yet, in contrast to sitting, infants seldom coupled looking and object manipulation in prone. Although the "tummy time" campaign urges parents to place infants in a prone posture for play (Chizawsky & Scott-Findlay, 2005), manual and oral exploration were less frequent compared to supine and sitting postures. Practicing prone skills may be useful for promoting muscle growth and deterring the flattening of infants' soft skulls (Graham, 2006), but for object exploration the prone position is suboptimal.

Supine

In a supine posture, infants face a different set of postural challenges. Directing arm movements while on their backs requires infants to continuously generate torque against gravity, demanding greater motor control (Out et al., 1998; Savelsbergh & van der Kamp, 1994). Neck control is more difficult in a supine posture; eye gaze and tracking are less stable (de Lima-Alvarez et al., 2013). Accordingly, as predicted, infants showed decrements in manual exploration. In supine, rotating, holding toys up for visual examination, and alternating mouthing and looking were reduced compared to a sitting position. Fingering and unimodal oral exploration were the most frequent coordinated actions while infants were supine. These behaviors, however, are less mature and informative (Lederman & Klatzky, 1987; Ruff, 1989; Ruff, McCarton, Kurtzberg, & Vaughan, 1984) and, because infants seldom coupled or alternated them with looking, provided solely tactile information about object properties. Moreover, other research has shown that manual exploration in supine is more likely to be disorganized and to contain extraneous "overflow" movements (Soska et al., 2012). Object play in a supine posture may comprise a bulk of infants' exploration in the few months of life, but the constraints on reach initiation (Savelsbergh & van der Kamp, 1994), head control (de Lima-Alvarez et al., 2013), and object exploration are real and numerous.

Sitting

Upright sitting confers an advantage to infants for exploration. Infants can initiate reaching and grasping more easily and with more control (de Graaf-Peters et al., 2007; Harbourne et al., 2013). As we predicted, every exploratory action was as high or higher while infants were in a sitting posture. Moreover, we observed the greatest frequencies of both alternated and simultaneously coordinated multimodal exploration in the sitting posture—coupling visual, manual, and oral modalities. From early infancy, intersensory redundancy directs infants' attention to useful social and physical information (Bahrick et al., 2004) and seems to play a critical role in object learning (Baumgartner & Oakes, 2013; Eppler, 1995; Soska et al., 2010; Woods & Wilcox, 2013). Coordination of visual and manual exploration increases over early development (Bertenthal & von Hofsten, 1998; Soska et al., 2010), and acquiring the sitting posture promotes this coupling (Rochat, 1992; Rochat & Goubet, 1995).

One factor that we did not manipulate here, because the primary focus was on the effects of postural position, was whether infants were supported in sitting. Instead, as about half of the infants could not yet sit independently, we asked all of the parents to support their sitting infants. Surely, if parents had not held the nonsitters, they would have shown poorer object exploration than the self-sitters and likely toppled over (see Woods & Wilcox, 2013). Indeed, self-sitters in a supported sitting posture show more visual–manual exploration than nonsitters (Soska et al., 2010). Yet, in the current study, the supported sitting posture promoted better and more exploration than prone and supine postures, over and above the effects of age and sitting experience.

Are infants sensitive to the advantages of the sitting posture? By 7–9 months of age, after the onset of self-sitting, most infants can transition from prone or supine to sitting. Possibly, infants purposely place themselves into a sitting posture for exploration. An important venue for future research would be to examine how parents and infants structure real-time manual exploration at home and how the postural context for learning about objects varies and shifts over the first year of life.

Postural development expands opportunities for learning

How meaningful are postural differences in object exploration for long-term learning about the social and physical world? In the current study, in the 12 min of object play across posture conditions, we only found approximately 10–15 more manual actions and 30–45 sec more of oral or visual exploration while infants were sitting. Nonetheless, over the weeks and months that infants explore and learn about objects, such minor differences can compound immensely. Assuming that by 5 months of age, infants may spend 6 h of each day active and alert (Roffwarg, Muzio, & Dement, 1966), they may produce over 400 more manual actions and gain 22 more minutes per day of visual examination while in a sitting posture compared to lying prone and supine combined. If infants' at-home exploration is driving object knowledge and social learning (e.g., Eppler, 1995; Sommerville et al., 2008; Soska et al., 2010), then these small shifts in posture can promote greater opportunities for learning.

Do our findings suggest that parents should bolster their infants' time spent sitting? On the one hand, recent work demonstrates that early supplementation of infants' postural and exploratory skills can produce advancements in manual actions up to 2 months after the original, short intervention (Lobo & Galloway, 2008, 2012; Needham, Barrett, & Peterman,2002). And in some cultures, the attainment of sitting and other motor skills may be advanced relative to western norms (Adolph, Karasik,

& Tamis-LeMonda, 2010). However, to date, we know of no evidence for long-term cognitive or social benefits of training posture or exploration skills in typically developing children. There may be a ceiling on how much exploration infants require to gain specific object or social knowledge, and advancing the time course beyond where it might typically occur may confer no gain.

On the other hand, for children at risk of delays in motor development—cerebral palsy, preterm birth, familial risk of autism—supplementing postural experiences may be immensely valuable. For instance, infants at high risk of autism initiate sitting less often than low risk infants (Nickel, Thatcher, Keller, Wozniak, & Iverson, 2013). Moreover, the deleterious, biomechanical effects of supine and prone postures may be exacerbated for infants at risk of motor delays, given that they already have difficulties initiating reaching and maintaining postural control (Deffeyes et al., 2009; Fallang, Saugstad, & Hadders-Algra, 2003; Hadders-Algra et al., 2007). Indeed, early-occurring interventions, focused on postural development in infants with movement disorders, have been effective in shifting infants' motor and cognitive abilities toward trajectories more like those of typically developing infants (Heathcock, Lobo, & Galloway, 2008; Lobo, Harbourne, Dusing, & McCoy, 2013). Promoting more sitting time might ameliorate the negative effects of motor delays on cognitive and social skills and the ensuing, bidirectional impacts on further exploratory development.

CONCLUSIONS

Our findings support contentions that sitting is an important setting event in exploratory development and learning about the social and physical world (Adolph & Berger, 2006; Bertenthal & von Hofsten, 1998). The results expand on related work examining the quality of infants' reaching and grasping in different postural contexts. But, in the current study, we focused on object exploration and showed that real-time changes in posture affect the information infants obtain about objects. The present work affirms the importance of studying infant exploration and learning in a larger perception–action context. This "action systems" approach as advocated by Reed (1982) is imperative to gain a richer understanding of learning in early infancy.

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