# Sensitivity to Visual-Tactile Colocation on the Body Prior to Skilled Reaching in Early Infancy

Jannath Begum Ali [iD]
*Birkbeck, University of London and Goldsmiths, University of London*

Rhiannon L. Thomas [iD]
*Goldsmiths, University of London and University College London*

Stephanie Mullen Raymond
*Goldsmiths, University of London*

Andrew J. Bremner [iD]
*Goldsmiths, University of London and University of Birmingham*

Two experiments examined perceptual colocation of visual and tactile stimuli in young infants. Experiment 1 compared 4- ($n = 15$) and 6-month-old ($n = 12$) infants' visual preferences for visual-tactile stimulus pairs presented across the same or different feet. The 4- and 6-month-olds showed, respectively, preferences for colocated and noncolocated conditions, demonstrating sensitivity to visual-tactile colocation on their feet. This extends previous findings of visual-tactile perceptual colocation on the hands in older infants. Control conditions excluded the possibility that both 6- (Experiment 1), and 4-month-olds (Experiment 2, $n = 12$) perceived colocation on the basis of an undifferentiated supramodal coding of spatial distance between stimuli. Bimodal perception of visual-tactile colocation is available by 4 months of age, that is, prior to the development of skilled reaching.

Arriving in the outside world, the newborn infant has to determine how their tactile spatial representations formed *in utero* relate to the much richer and generally more distant spatial environment newly offered up by hearing, olfaction, and vision. How do they make sense of this multitude of sensory inputs, learning which stimuli to attribute to common environmental events or objects and which to segregate (e.g., Körding et al., 2007; Rohe & Noppeney, 2015)? In this article, we report the findings of a study designed to determine whether young human infants can solve one aspect of this cross-modal binding problem. Specifically, we set out to establish whether infants can determine whether tactile and visual stimuli are arising from the same or different places on the body. A sense of visual-tactile colocation on the body is a crucial component of an ability to perceive the multisensory coherence (or lack of coherence) not just of events

occurring on the body (e.g., the kinds of sensations which occur when a parent visibly reaches out and brushes an infant's hand), but also the ability to sense one's own body and limbs per se (e.g., Lewkowicz & Bremner, 2020).

The last 40 years of research into multisensory perception in infants has focused largely on infants' sensitivity to visual-auditory links (e.g., Bahrick & Lickliter, 2012; Jaime, Bahrick, & Lickliter, 2010; Lewkowicz & Ghazanfar, 2009; Lewkowicz, Leo, & Simion, 2010). However, more recently a number of investigations have yielded new knowledge about how infants come to perceive relations between touch and other sensory inputs (e.g., Filippetti, Johnson, Lloyd-Fox, Dragovic, & Farroni, 2013; Freier, Mason, & Bremner, 2016; Thomas et al., 2018; Zmyj, Jank, Schütz-Bosbach, & Daum, 2011). This research sheds light on the development of the multisensory interactions underpinning representations of one's own body and its relation to the world around us. As

adults, our representations of limb and body positions result from the combination and integration of direct sources of information about the body such as touch and proprioception with visual and auditory information (Makin, Holmes, & Ehrsson, 2008). Mature body representations are thus reliant on a network of multisensory cortical and subcortical areas, including particularly premotor cortex, posterior parietal cortex, and the putamen (Holmes & Spence, 2004), which must translate inputs from each sense modality into common spatiotemporal codes.

Current views of multisensory development (e.g., Bahrick & Lickliter, 2012) argue that spatial and temporal properties of sensory stimulation are amodal and thus easily abstracted across the senses by the young infant. However, this view is largely based on evidence concerning the development of visual-auditory links in early life, and recent findings suggest that there may be more of a computational challenge involved in infants' acquisition of a common space for perceiving tactile visual spatiotemporal links. For instance, before 10 months of age, infants show little tendency to orient their eyes to touches presented to the hands (Bremner, Mareschal, Lloyd-Fox, & Spence, 2008). Furthermore, Begum Ali, Spence, and Bremner (2015) have found that infants do not appear to represent touches in visual external spatial coordinates until 6 months of age, and an ability to remap perceptual representations of the location of a touch in external space across changes in the visual posture of the arms appears to emerge between 6 and 10 months of age (Bremner, Mareschal, et al., 2008; Rigato, Begum Ali, Van Velzen, & Bremner, 2014).

The above studies have shown an extended developmental trajectory for visual-tactile interactions. However, these findings sit in contrast to other studies indicating that infants much younger than 6 months of age are sensitive to visual-tactile information. For instance, Filippetti and colleagues (Filippetti et al., 2013; Filippetti, Orioli, Johnson, & Farroni, 2015) have presented evidence that even newborns are capable of detecting visual-tactile synchronies and colocation between tactile stimuli on their own face and visual stimuli on pseudo-mirror-images of their faces.

And, so we have at present a rather confused picture of visual-tactile development in early life, with studies investigating tactile localization in visual/external space demonstrating protracted development across the first year (Begum Ali et al., 2015; Bremner, Mareschal, et al., 2008; Rigato et al., 2014), whereas studies probing infants' sensitivity to visual-tactile colocation indicate much earlier

competence (e.g., Filippetti et al., 2015; see also Bahrick & Watson, 1985; Rochat, 1998; Rochat & Morgan, 1995). Crucial to reconciling these findings is a consideration of the different methods used in these experiments. Two particularly salient points arise as follows: (a) The earliest demonstrations of infants' (newborns') sensitivity to visual-tactile colocation have involved visual-tactile pairings presented on the face (Filippetti et al., 2015), whereas tactile localization studies showing later developing ability presented tactile stimuli on the hands or feet; (b) Studies demonstrating sensitivity to visual-tactile colocation before 6 months of age have presented infants with visual-tactile stimuli in which the visual cue is displayed on a video screen of their limbs or face well beyond the bounds of their own bodies, in external space. In contrast, the studies demonstrating limitations in tactile orienting (e.g., Begum Ali et al., 2015) involved scenarios in which tactile stimuli were presented directly on the body. One clear way to potentially resolve these conflicting findings is thus to hypothesize that, prior to 6 months of age, infants have difficulty coordinating visual and tactile spatial coordinate frames in personal space (see Bremner, Holmes, & Spence, 2008). In order to test this, we need to determine whether young infants can colocate visual and tactile stimuli on their own limbs (hands or feet). Given recent findings that an ability to refer touches to locations in visual external space develops between 4 and 6 months of age (Begum Ali et al., 2015), it makes sense to compare those particular age groups.

Thus, in this study, we examined whether an ability to perceive visual-tactile colocation develops prior to 6 months of age, by comparing 4- and 6-month-olds' sensitivity to visual-tactile colocation. As well as evidence from Begum Ali et al. (2015) showing that external visual space influences 6-, but not 4-month-olds' tactile localization, there is strong evidence that the development of an ability to refer touch to external spatial coordinates is sensitive to early visual experience during this period. It has been established for some time that congenitally blind adults show less interference of external spatial coordinates when locating touches on the body (Röder, Rösler, & Spence, 2004). However, one particular study with congenitally blind children who had had cataracts removed in the first months of life, indicates that visual experience plays a particular role only after 4 months of age: If cataracts were removed before 5 months of age, tactile localization developed typically (Azañón, Camacho, Morales, & Longo, 2018; see also Ley, Bottari, Shenoy, Kekunnaya, & Röder, 2013). On the basis of

these findings, we predicted that 4-month-olds would not have gained experience of visual-tactile spatial colocation, and would therefore not be able to differentiate colocated and noncolocated visual-tactile stimuli. Commensurate with this prediction, the emergence of successful visually targeted reaching between 4 and 6 months is a likely candidate for mediating the spatial coordination of vision and touch through sensorimotor experience. Four-month-olds infants are typically prereaching and will therefore have little active experience (certainly less than that of 6-month-olds) of the colocated visual-tactile experiences which come along with picking up visually targeted objects.

To test 4- and 6-month-old infants' sensitivity to visual-tactile colocation in this study, we used a task developed by Freier et al. (2016). Freier et al. presented concurrent visual and tactile stimuli to the hands of 6- and 10-month-old infants. These visual-tactile paired stimulations either occurred on the same hand or different hands. Both age groups differentiated between these conditions, preferring to look longer at their hands when the visual and tactile stimuli were on separate hands. This study also introduced additional conditions to test alternative accounts of sensitivity to visual-tactile colocation in this task. It remains unclear whether the 6- and 10-month-old infants in Freier et al.'s study bound the separate visual and tactile stimuli into a single perceptual event. In adults, temporally synchronous and spatially colocated stimuli have been shown to result in the perception of a multisensory event with a single origin (e.g., Körding et al., 2007). But, there is a range of other ways in which we can interpret the visual preferences shown in Freier et al.'s study. It might be that discrimination of visual-tactile colocated and noncolocated trials was based on a perception of a single bound multisensory event on colocated trials, versus two unbound unisensory (tactile and a visual) stimuli on noncolocated trials. But there are other possibilities. In Experiment 1, we sought to rule out one of these alternative explanations, namely, that the infants differentiated colocated and noncolocated stimuli on the basis of a supramodal spatial code: it may be that infants preferred the noncolocated trials because the stimuli, regardless of modality, were spread across a larger portion of space (across two hands).

## Experiment 1

In Experiment 1, we adopted a similar paradigm to that used by Freier et al. (2016), presenting colocated and noncolocated visual tactile stimuli (via computer-controlled LEDs and tactors) to 4- and 6-month-old infants. Piloting with the younger age group indicated that 4-month-olds were less inclined to place their hands in the field of view. As such we decided to change the placement of the visual-tactile stimuli to the feet for both age groups. And, so infants were presented with visual-tactile trials in which lights and vibrotactile stimuli appeared on the same foot (colocated condition) or across different feet (noncolocated condition). In order to determine whether the infants were locating the relative location of the visual and tactile stimuli on the basis of a supramodal versus a bimodal code, we included a control condition in which either auditory or tactile stimuli were presented on both hands synchronously (see Thomas et al., 2018). Our predictions were that the 6-month-olds, but not the 4-month-old infants would look longer at spatially noncolocated than at colocated visual-tactile trials, as in Freier et al. (2016). If the 6-month-olds also exhibited significantly greater duration of looking in the noncolocated compared to the control trials this would suggest that their visual preference for the noncolocated condition was due to the lack of colocation crossmodally rather than because these signals are spread across a larger space irrespective of modality.

## Methods

### Participants

Sixteen 4-month-olds (8 males), aged between 102 and 149 days ($M = 121$ days; $SD = 14$ days) took part in this study. One female participant was excluded from the final analyses due to an equipment malfunction. The age range of the remaining fifteen 4-month-olds was 102–149 days ($M =$ 120 days; $SD = 14$ days). The older age group included twelve 6-month-olds (5 male), aged between 182 and 231 days ($M = 196$ days; $SD = 14$ days). All infants were recruited from within South East London, an ethnically diverse location, in the Spring of 2014 (January–April). Informed consent was obtained from the parents before commencing the study. The testing took place only if the infant was awake and appeared to be in an alert and content state. Ethical approval was gained from the Research Ethics Committee of the Department of Psychology, Goldsmiths, University of London.

In both Experiment 1 and Experiment 2, the minimum sample size was determined apriori to be 12

infants per age group. The published findings in Freier et al. (2016) yielded effect sizes (of the infants' looking preferences to noncolocated over colocated trials) which were medium to large ($d_z$ = 0.6–$d_z$ = 1.2). Therefore, assuming a compromise effect size of $d_z$ = 0.9, with a power set at 0.8 and an alpha set at .05, yields a required sample size of 12 (according to G*Power; Faul, Erdfelder, Lang, & Buchner, 2007). Setting 12 infants as our minimum sample size led to the collection of *at least* 12 infants in each group tested and retained for analysis.

## Design

The infants were presented with trials in which 10 stimulus pairs were delivered in sequence across both feet. Each of these stimulus pairs (10 per trial) comprised visual flashes and vibrotactile stimuli applied to the soles of the feet presented in synchrony for 700 ms. There was a 1,500 ms interstimulus interval between the presentation of each stimulus pair. Each trial containing 10 stimulus pairs thus lasted for 20.5 s in total, during which we recorded the infants' total looking duration to their feet.

There were three conditions, presented across successive trials, which determined the nature of the stimulus pairs presented in each trial: Colocated, Noncolocated, and Control (see Figure 1). During Colocated trials, each of the 10 stimulus pairs comprised simultaneously presented visual and tactile stimuli on the same foot. Thus each event in Colocated trials comprised visual and tactile stimuli sharing the same spatial location on the body. In comparison, for Noncolocated trials, for each of the 10 stimulus pairs the visual and tactile stimuli were presented simultaneously on *different* feet (and did not share the same spatial location on any event during the trial). Finally, for Control trials, for any given stimulus pair, one pair of stimuli from a single modality only (either visual or tactile) was presented to both feet (see Figure 1). The order of presentation of double tactile or double visual pairs was randomized within each control trial. The infants' overall looking behavior (to the feet) across each trial was measured, and average looking in each condition was compared across the successively presented conditions to determine looking preferences between conditions.

To be included in the analyses, participants had to complete one block of each test condition (thus a total of 30 stimulations). The order of the three test conditions (Colocated/Noncolocated/Control) was fully counterbalanced between participants,

## Stimuli and Apparatus

The infants were seated in a specialist baby chair. The seat was reclined in a horizontal position with the back-rest parallel to the floor. Adjustable straps were used to secure the infant in the seat. Cotton padding and a head-rest were used to secure the posture of the infant's trunk. All testing took place in a dimly lit room, to discourage infants from looking at their surroundings. An infrared video camera located 80 cm in front of the chair and 60 cm above the torso of the infant recorded each infant's looking behavior. Video data were recorded for offline coding.

The vibrotactile stimuli were delivered by two voice coil transducers (tactors) driven by a 220 Hz sine wave and controlled by custom software scripted in E-Prime. Additionally, the E-Prime script sent signals that were time-locked to the onset and offset of the vibrotactile stimuli to a video titler so that the infants' stimulus-locked behavior could be observed and coded. Any noise emitted by the tactors was masked with gray noise played from a centrally placed loudspeaker. This masked sound cues for both the infant and experimenter.

As described in the following section, the infants' feet were held roughly 10 cm apart during stimulus presentation. This resulted in a separation of ~9–13 degrees of visual angle. Thus if an infant was fixating one of their feet, the other foot (and any visual stimulus on it) will have fallen well within the field of view.

## Procedure

The infants were secured into the baby seat. Following this, the tactors were positioned on the soles of their feet and secured with cohesive bandage before white cotton scratch mittens were placed over the feet. The scratch mittens contained LED assemblies which were positioned (and sewn into the mittens) so that lights could be presented from the top of the infant's feet. The scratch mittens were secured in place with Velcro straps.

On each trial, an experimenter held onto the infant's legs maintaining approximately 10 cm between the feet during stimulus presentations. The experimenter then engaged in a game of peek-a-boo with the infant's feet (using the infant's feet, held by the ankles to cover the experimenter's eyes and part of the face while "hiding" and separating the feet to reveal their face). This was carried out so as to engage the infant and direct their gaze to their feet. After three "peek-a-boos," the experimenter
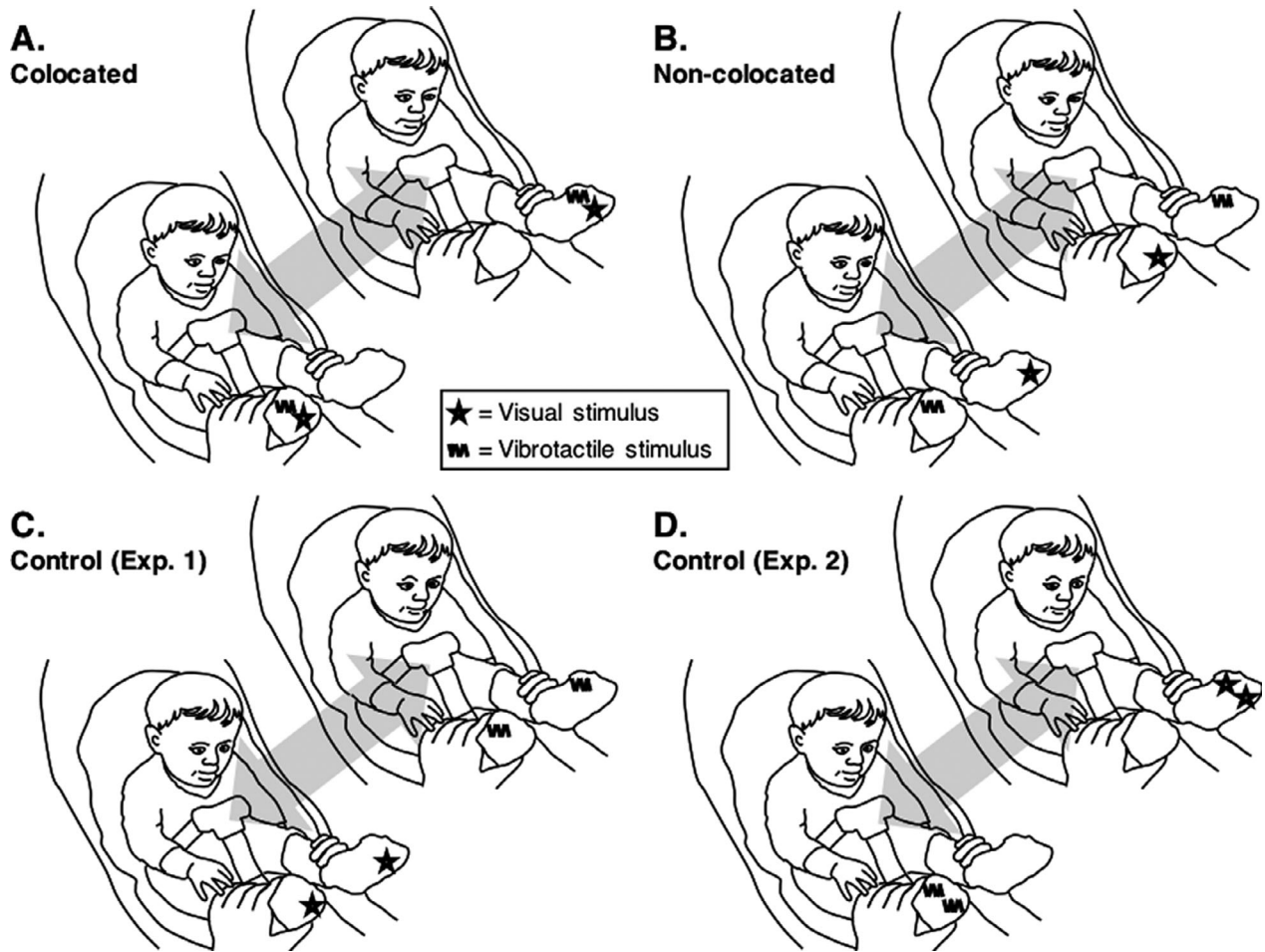
*Figure 1.* Experiment 1 set up. Panel A corresponds to the Colocated condition, where visual and tactile stimuli were applied to the same foot. Panel B corresponds to the Noncolocated condition, where visual and tactile stimuli were applied to *different* feet. Panel C corresponds to the Control condition, where five pairs of visual stimuli and five pairs of tactile stimuli were applied to both feet. Pairs of stimuli (visual and tactile) were administered to the feet synchronously for 700 ms. Following an interstimulus interval of 1,500 ms, the pairs of stimuli were then administered to the opposite foot. This alternation between feet in the Colocated and Noncolocated conditions continued for 10 pairs of stimuli. For the Control condition, stimuli were applied to both feet throughout and it was the *type* of stimuli (visual or tactile) that alternated between stimulations.

would move out of sight, still holding the infant's feet in place (10 cm apart) for the duration of the trial. If the infant remained looking at their feet at this time, a second experimenter initiated a trial. If the infant was not looking at their feet, the second experimenter signaled (via an intercom) for the first experimenter to continue engaging with the infant. Once again, this researcher would engage in a series of three peek-a-boos (one set comprised of three peek-a-boos) before moving out of sight. The second experimenter would then initiate the program. On all trials, two sets of peek-a-boo (six peek-a-boos) were sufficient to direct the infant's gaze to their feet to begin a trial.

In the time during a trial (each trial comprised a series of 10 stimulus pairs) the experimenter stayed out of sight and oriented her face to the floor in order not to distract the infant. Once a trial had reached its completion, the second experimenter signaled via intercom for the first experimenter to redirect the infant's attention to their feet through a game of peek-a-boo. If the infant became fussy, they were entertained with songs or games of peek-a-boo between trials until they were settled enough to continue with the study. Participants completed a minimum of one trial for each condition and maximum of three trials per condition.

### Data Coding and Analysis

The infants' looking behavior to the visual and tactile stimuli was coded from the video records in

Quicktime 7 Player for Macintosh (using frame onset and offset times, calculating the difference between the number of frames before converting to milliseconds). Raters were blind to the condition, but were provided with stimulus onset and offset information. Infants were considered to be looking at the stimuli if they were looking at either their left or right foot for any length of time during a trial. The dependent variable, looking duration, was thus operationalized as the duration of time, in the fixed duration trials (averaged across condition where appropriate), for which infants were looking at one of their feet (durations of looking at left and right feet were summed). Any periods of time during inspection of the feet where the infants blinked or had their eyes closed were not included in the total looking duration to the feet for that trial. Periods of time during which the infants shifted their gaze between their feet (left to right or vice versa) were included in the total looking duration for that trial. If the infants shifted their gaze from a foot to elsewhere (e.g., their hand, the room) before looking at the other foot, the period of time from which the gaze shifted away until it next returned to a foot was not included in the total looking duration for that trial. Given that we are investigating endogenous perceptual preferences for multisensory stimulus pairs in which the tactile component is perceptible in the absence of visual inspection, it was possible that even short inspections could be driven by perceptual preferences. As such, we employed no minimum look duration criterion.

Only a subset of infants proceeded to second and third blocks before testing was terminated. All included infants completed one block. Eleven of the 4-month-olds proceeded to the second block, and eight of those completed block three. Only two of the 6-month-old infants proceeded to a second block, and no 6-month-olds completed block three. In order to obtain a valid comparison of looking times across age groups and conditions, we restricted our analyses to the first block of trials.

A second rater coded a proportion of all the videos of participants which were included in the analyses reported in the results section (12 of 27 infants, 44%) evenly spread across the two age groups. Inter-rater reliability was high for the Colocated, Noncolocated and Control conditions; Cronbach's α was .92, .89, and .95, respectively.

## Results

A 3 × 2 mixed measures analysis of variance of looking duration with the within-participants factor of Condition (Colocated/Noncolocated/Control) and the between-participants factor of Age (4-month-olds/6-month-olds) was conducted. This revealed a significant main effect of Condition, $F(2, 50) = 7.55$, $p = .001$, $\eta_p^2 = .23$, (Colocated: $M = 12.45$ s, $SE = 1.2$; Noncolocated: $M = 12.81$ s, $SE = 1.04$; Control: $M = 9.97$ s, $SE = 0.91$). Additionally, a significant interaction of Condition × Age was seen, $F(2, 50) = 11.52$, $p < .001$, $\eta_p^2 = .32$. Finally, a main effect of Age approached significance, $F(2, 50) = 3.27$, $p = .07$, $\eta_p^2 = .12$, indicating that the 4-month-olds ($M = 39.57$ s, $SE = 4.27$) tended to look longer at their feet than the 6-month-olds ($M = 29.81$, $SE = 2.2$) across all conditions (see Table 1 and Figure 2).

To explore the significant interaction of Condition × Age, we conducted six post hoc comparisons to examine effects of Condition within each Age group separately (the significance level of each test was Bonferroni corrected to $p = .008$ to adjust for Type I error). In the 6-month-old age group, the infants looked longer at the Noncolocated than Colocated trials, $t(11) = 4.66$, $p < .001$, $d_z = 1.26$, replicating the findings of Freier et al. (2016). Additionally, as expected, infants spent more time looking at the stimuli in the Noncolocated condition than the Control condition, $t(11) = 4.67$, $p < .001$, $d_z = 1.64$. There was no significant difference in 6-month-olds' looking times between the Colocated and Control conditions, $t(11) = 0.2$, $p = .84$, $d_z = 0.08$.

The above comparisons were also conducted with the 4-month-old group. Contrary to the pattern shown by the 6-month-olds, the 4-month-olds looked for longer in the Colocated than the Noncolocated condition, $t(14) = 3.13$, $p = .007$, $d_z = 0.5$. They also looked for longer in the Colocated than the Control condition, $t(14) = 4.37$, $p = .001$, $d_z = 0.76$. No reliable difference in looking time was observed between the Noncolocated and Control conditions, $t(14) = 1.02$, $p = .4$, $d_z = 0.2$.

Table 1

*Means (and SDs) of Duration of Looking to the Feet in Seconds by Condition and Age Group in Experiments 1 and 2*

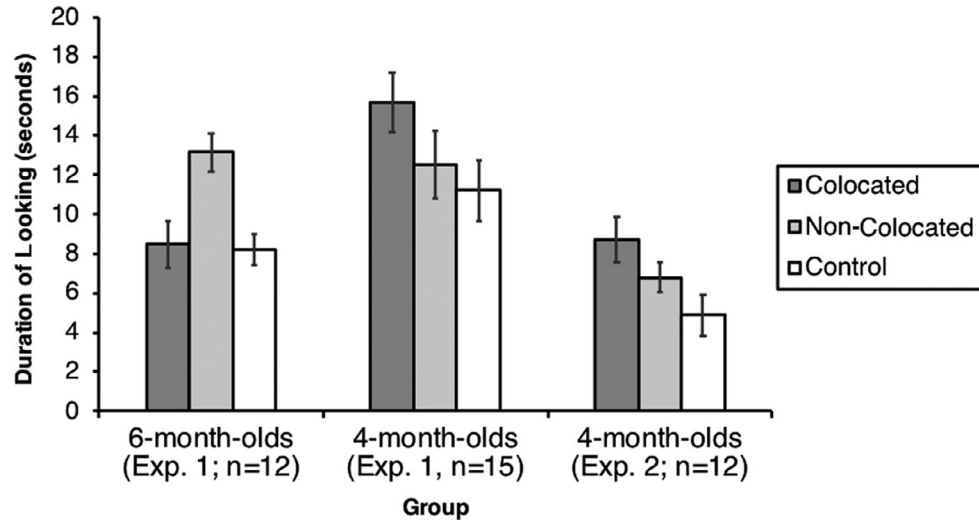|  | Experiment 1 | | Experiment 2 |
|  | 4-month-olds | 6-month-olds | 4-month-olds |
| --- | --- | --- | --- |
| Colocated | 15.64 (5.83) | 8.46 (4.09) | 8.72 (3.9) |
| Noncolocated | 12.53 (6.74) | 13.15 (3.36) | 6.8 (2.51) |
| Control | 11.39 (5.54) | 8.2 (2.68) | 4.88 (3.59) |

*Figure 2.* Mean looking duration (at the feet) of the 4- and 6-month-olds in Experiment 1, and the 4-month-olds in Experiment 2, compared across stimulus presentation conditions. Errors bars indicate the standard error of the mean.

*Discussion*

Experiment 1 confirms findings of Freier et al. (2016) that 6-month-old infants can reliably distinguish between situations in which visual-tactile stimuli are presented in the same region of space (co-located) versus when they are presented across different locations (noncolocated). However, Experiment 1 shows for the first time in infancy that this ability extends to the feet in addition to the hands (Freier et al., 2016). Further to this, we have also found, contrary to our predictions, that 4-month-old infants can distinguish between co-located and noncolocated visual-tactile stimuli on their feet. This indicates that infants can learn about visual-tactile colocation prior to the influence of external spatial coordinates on tactile localization (Begum Ali et al., 2015), and also prior to the development of skilled visually targeted reaching, which typically develops from 5 months of age (including reaching with the feet, Galloway & Thelen, 2004).

The control condition in this study presented concurrent unimodal stimuli across both feet. This mimicked the Noncolocated condition in terms of the spatial distribution of stimuli, but presented those stimuli *within* a sensory modality (either visual or tactile) rather than *across* sensory modalities. By comparing these two conditions, we tested infant's preferences for viewing unimodal versus bimodal stimuli separated in space. If the infants were merely attracted by noncolocated, or more widely spread stimuli irrespective of modality (i.e., if they coded these stimuli supramodally), we

should not have seen any differences in looking behavior between these conditions. However, our results showed that 6-month-olds spent a significantly greater time observing the bimodal dislocated stimuli (Noncolocated condition) compared to unimodal dislocated stimuli (Control condition). As such, the larger spatial distribution of stimuli in the Noncolocated condition (compared to the Colocated condition) is not an adequate explanation of the infants' looking preferences. Therefore, we explain the 6-month-olds' novelty preference in terms of a representation of the relative location of tactile and visual stimuli in events which are perceived as bimodal.

The 4-month-olds demonstrated a visual preference for the Colocated condition (in which the visual and the tactile stimuli were presented on the same foot) relative to when the stimuli occurred across both feet (Noncolocated condition), suggesting an ability to distinguish between visual-tactile stimulus presentations on the basis of their colocation (or noncolocation).

It is important to remember that discrimination of noncolocated and colocated visual-tactile events by 4-month-old infants necessitates an explanation which appeals to their ability to register the spatial relations between tactile and visual stimuli at some level of multisensory processing. However, the current data do not allow us to differentiate between accounts of such ability in terms of the processing of multisensory relations between touch and vision, or in terms of a response to the supramodal spatial extent of stimuli (i.e., their spatial locations/extent

independently of modality). The 4-month-olds showed a preference for the condition in which the visual-tactile stimuli occurred on the same foot and were thus co-located. Considering an account in terms of supramodal coding of location, it is possible that infants of this young age showed a preference for this condition because the two stimuli occurred on the same foot, irrespective of their modality. This explanation is not ruled out by the control condition in this study which was included to rule out a preference for a wider spread of stimuli in space.

In order to determine whether 4-month-olds can colocate visual and tactile stimuli on the basis of their bimodal spatial relations or on the basis of a supramodal spatial code, we conducted a further study (Experiment 2) to replicate our findings with 4-month-old infants from Experiment 1, but this time including a control condition which enabled us to differentiate between bimodal and supramodal accounts of 4-month-olds' visual-tactile colocation abilities.

## Experiment 2

Experiment 2 examined whether the visual preference for colocated visual-tactile stimuli on the body shown by 4-month-old infants was due to the presence in that condition of two stimuli concurrently presented to one foot, irrespective of sensory modality. This supramodal clustering of stimulation is present only in the colocated condition of Experiment 1, and could have been preferred by the infants, for instance, as a result of the two stimuli capturing attention to a single location. The Control condition in Experiment 1 could not rule out a supramodal explanation of these findings and, so we developed a new Control condition for Experiment 2. Specifically, this condition involved presenting two unimodal stimuli on one limb (see Figure 1 and in the below section for further details). If the 4-month-olds' visual preference for colocated visual-tactile stimuli over noncolocated stimuli is based on a supramodal clustering of stimuli in the same place we would expect to find no preference for the Colocated condition over the Control condition. However, if the infants' preference for the Colocated over the Noncolocated condition is based in a bimodal (visual-tactile) spatial code then we would expect them to prefer the Colocated over the Control condition. As such we planned two comparisons in Experiment 2: (a) between the Colocated and the Noncolocated conditions where we expected to replicate the finding of longer looking in the Colocated condition, and (b) between the Colocated and the Control condition, where we had no specific expectation, but where longer looking at the Colocated condition would indicate the role of a bimodal code in 4-month-olds' sensitivity to visual-tactile colocation.

### Methods

#### Participants

Seventeen 4-month-olds (8 males) aged between 113 and 152 days ($M = 128$ days, $SD = 12$ days) participated in the study. Five participants (1 male) were excluded from the final analyses due to experimental error ($n = 1$), parental interference ($n = 1$) or fussy behavior during the testing session which resulted in not looking at the stimuli ($n = 3$). The age range of the remaining 12 participants was between 104 and 152 days ($M = 130$ days, $SD = 13$ days). Once again infants in this study were recruited from the same ethnically diverse areas of South East London as in Experiment 1. The infants were recruited and tested in March–June of 2015. Informed consent was obtained from the parents before commencing the study. The testing took place only if the infant was awake and appeared to be in an alert and content state. Ethical approval was gained from the Ethics Committee of the Department of Psychology, Goldsmiths, University of London.

#### Design

The design of Experiment 2 was almost identical to that of Experiment 1, with one notable difference: the Control condition now consisted of alternating pairs of stimuli from a single modality, visual or tactile presented to the *same* foot (see Figure 1). For example, a pair of visual stimuli was presented to the right foot followed by a pair of tactile stimuli presented to the left foot. The Colocated (visual and tactile stimuli were presented simultaneously on the same foot) and Noncolocated (the visual and tactile stimuli were presented simultaneously on *different* feet) conditions were the same as Experiment 1.

#### Apparatus and Procedure

Every effort was made to carry out the procedure in an identical way to Experiment 1. However, it is important to note that a different Experimenter

played the role of interacting with the infant and holding their feet, through the session.

*Data Coding and Analysis*

Infants' looking behavior to the visual and tactile stimuli was coded in the same way as in Experiment 1. A second rater coded a proportion of all videos (12 infants, 70%). Inter-rater reliability was high for the Colocated, Noncolocated and Control conditions; Cronbach's alpha at .92, .76, and .98 respectively. All infants tested completed two blocks of trials, and so looking duration in each condition was averaged across blocks 1 and 2.

As explained earlier, our analysis was two planned comparisons of looking duration between: (a) the Colocated and Noncolocated condition (significantly longer looking was expected for the Colocated condition, replicating the finding of Experiment 1), and (b) the Colocated and Control condition (longer looking in the Colocated condition would indicate that sensitivity to visual-tactile colocation is based on a bimodal code in this age group). The standard significance level of .05 was used for these comparisons (Howell, 1997).

*Results*

As shown in Figure 2, the 4-month-olds in Experiment 2, the pattern of mean looking duration indicates longer looking in the Colocated condition than the other two conditions, and longer looking in the Noncolocated condition than the Control condition. There also appears to be shorter looking duration across conditions in the 4-month-olds tested in Experiment 2, than the same age group tested in Experiment 1. There are a number of differences between Experiments 1 and 2 which would make such an effect hard to interpret. First, in this Experiment (Experiment 2), 4-month-olds' preferences were assessed across two blocks rather than one block as in Experiment 1 (this may have led to a decrease in their looking through habituation). The two experiments were also run at quite different times of year, and by different experimenters. Because the experimenter engages infants in a face-to-face game throughout these experiments, there is a considerable social component interexperimenter differences in which are likely to affect looking duration, the degree of compliance, and the duration of testing. Given these factors we have not made inferential comparisons between experiments, instead relying on within experiment tests concerning the pattern of findings between conditions. As

indicated earlier, we planned two comparisons (paired sample *t*-tests) within this data set, which established that the infants' looked reliably longer in the Colocated compared to the Noncolocated conditions, $t(11) = 2.28$, $p = .043$, $d_z = 0.66$, and in the Colocated compared to the Control condition, $t(11) = 5.26$, $p < .001$, $d_z = 1.52$.

Two infants in this 4-month-old sample presented a looking duration of 0 s for one condition. We decided to include these participants in our analyses as, in this task, there are nonvisual aspects of the trials (the tactile stimuli) which ensure that the infants are aware that trials are being presented, and as the feet only occupy a relatively small area of the infants' visual fields, it is quite possible to form a preference between conditions based on peripheral inspection while demonstrating zero looking in one condition. Our inclusion of these particular two infants in the current experiment was further informed by the fact that they completed the experiment without fussy behavior, and that the condition where they scored 0 looking time was not the first or last trial. Nonetheless, when performing the same planned comparisons as reported earlier, but excluding these participants (yielding = 10), revealed the same outcome with longer looking in the Colocated than the Noncolocated condition, $t(9) = 3.12$, $p = .012$, $d_z = .85$, and longer looking in the Colocated than the Control condition, $t(9) = 5.26$, $p = .001$, $d_z = 1.18$.

*Discussion*

Overall, the findings of Experiment 2 show that 4-month-old infants prefer to look at visual-tactile events occurring on a single foot (Colocated trials), over simultaneous visual and tactile stimuli separated across the feet (Noncolocated trials), and unisensory stimulus pairs occurring on the same foot and alternating between visual and tactile modalities (Control trials; see Figure 2). This replicates and confirms the finding of Experiment 1, that 4-month-old infants are sensitive to visual-tactile spatial colocation on their bodies, and furthermore shows that this sensitivity to visual-tactile colocation is based on a bimodal rather than a supramodal spatial code.

## General discussion

These two experiments have shown that infants at both 4 and 6 months of age are able to distinguish between bimodal visual-tactile events on the basis

of whether the tactile and visual stimuli are present in the same place in bodily space—in this case, whether visual and tactile stimuli were colocated on the same foot or not. Previous research (e.g., Freier et al., 2016) has demonstrated an ability to colocate visual and tactile stimuli on the same hand in 6- and 10-month-old infants, but this is the first study to demonstrate visual-tactile colocation in bodily space in younger (4-month-old) infants. Indeed, the demonstrations of an ability to distinguish between colocated and noncolocated visual-tactile stimulus pairs on the body in the current report align with other published results using the same method (Freier et al., 2016; Thomas et al., 2017), across multiple age groups, and across both visual-tactile and auditory tactile stimulus combinations to provide a highly robust body of evidence indicating an ability to perceive multisensory colocation on the body from 4 months of age.

Evidence of the ability to colocate visual-tactile stimuli in 4-month-old infants is particularly important given that recent findings show that at 4-month infants do not yet refer touches on the limbs to external (visual) spatial coordinates (Begum Ali et al., 2015): Although adults, late blind adults, children, and 6-month-old infants show more difficulty in locating tactile stimuli on the limbs when those limbs are in unfamiliar positions with respect to visual (external) space (e.g., with the arms crossed over; Begum Ali, Cowie, & Bremner, 2014; Begum Ali et al., 2015; Pagel, Heed, & Röder, 2009; Röder et al., 2004), Begum Ali et al. (2015) recently showed that 4-month-olds match the best performance of 6-month-olds in responding to touches to their feet, whether their legs are crossed over or uncrossed. In other words, 4-month-olds show no referral of touches to external visual space. Research with congenitally blind children and adults indicates that visual experience, specifically after 4 months of age, is critical to the typical development of external referral of touch (Azañón et al., 2018; Ley et al., 2013; Röder et al., 2004), and so the findings reported in this manuscript indicate that an ability to perceive colocation of tactile and visual stimuli on the body exists prior to the developmental visual remapping of touch to an external spatial frame of reference.

The current data provide some hints about how the multisensory interactions underlying body representations might develop. In studies like the current investigation, which demonstrates tactile-visual colocation ability (Filippetti et al., 2015; Freier et al., 2016; Zmyj et al., 2011), tactile stimuli are presented concurrently with visual stimuli. It is possible that the visual stimuli, by virtue of their synchrony with the tactile stimuli, provided enough of a spatial cue for 4-month-old infants to colocate visual and tactile stimuli in the same external reference frame, but that without that visual cue the tactile stimuli would have remained unreferred. Indeed, an ability at 4 months of age to use visual spatial events as an external spatial anchor for concurrent tactile stimuli may be a precursor to the developmental of an ability to locate a touch in external space in the absence of concurrent visual and/or auditory stimuli. Commensurate with predictions of Bahrick & Lickliter's intersensory redundancy hypothesis (e.g., Bahrick & Lickliter, 2000, 2012), it may be that spatial coding under multisensory conditions might lead to a later spatial ability under unisensory conditions.

The finding that an ability to perceive visual-tactile colocation on the body develops early in the first year aligns with evidence that newborn infants perceive spatial correspondences between touches on their faces and visual stimuli on a face viewed in extrapersonal space (Filippetti et al., 2015). An interesting question for future studies concerns the developmental relationship between these abilities. Do infants start by registering spatial correspondences between the senses independent of bodily space and later come to differentiate multisensory bodily space from multisensory external space? Such an account might possibly help to explain the later development of accurate responding to tactile stimuli when presented alone on the body (Begum Ali et al., 2015; Bremner, Mareschal, et al., 2008).

In Freier et al.'s (2016) previous study of visual-tactile colocation in bodily space, infants as young as 6 months of age demonstrated an ability to perceive visual-tactile colocation on the hands. Here, we have shown that this awareness of the colocation of visual and tactile stimuli generalizes to other body parts also, namely, the feet. Given that across our study and that of Freier et al.'s and our own study, the literature shows a competence at localizing tactile and visual events in a spatial frame of reference which appears to be generalized across the body, rather than being tied to the hands (with which it might be assumed that infants first come to learn about visual-tactile correspondences), it might be tempting to conclude that there is some degree of experience-independent preparation for colocalizing visual and tactile events within the same multisensory spatial framework; indeed, indications that even newborns have expectations about spatial colocation of touches and visual events on the face (Filippetti et al., 2015) support that view

also. However, even by 4 months of age, there has been opportunity to observe spatially coherent visual-tactile events on the body when those happen passively, but also in the context of active pre-reaching behaviors (Von Hofsten, 1984; e.g., when a reach is attempted but unsuccessful there is still a reasonable possibility that coordinated visual-tactile stimulation could result). Given that the first successful reaches happen with both hands and feet (Galloway & Thelen, 2004), our data could be consistent with the idea that infants can learn about visual-tactile colocation on their feet in the first 4 months of life. However, given that the first visually targeted reaches which approximate skilled reaching do not typically occur until just before 5 months of age (e.g., Galloway & Thelen, 2004; White, Castle, & Held, 1964), we can certainly conclude from our findings that, infants develop expectations about visual-tactile colocation prior to the development of the kind of skilled reaching which typifies the behavior of infants in the second half of the first year of life.

A role for experience in the development of visual-tactile spatial coordination is also suggested by the direction of visual preferences shown by the 4- and 6-month-old infants tested in our studies. The 6-month-olds tested in Experiment 1 demonstrated their discrimination of colocated and noncolocated visual-tactile events through a preference for the Noncolocated condition (where visual and tactile stimuli were presented on different feet and dislocated in space), whereas the younger 4-month-old infants preferred to view the Colocated condition, where the visual and tactile stimuli were presented on the *same* foot and colocated in space. This preference for colocation at 4 months and noncolocation at 6 months is consistent with the findings of similar studies (Freier et al., 2016; Thomas et al., 2018). Why might this be? We propose that developmental differences in patterns of looking behavior may reflect increasing experience with spatial relations between visual and tactile stimuli, which in turn drive a developmental shift from a preference for familiar to novel spatial relations among visual and tactile stimuli.

While visual preference techniques often work on the assumption that infants have a preference for novel over familiar stimuli, there is also evidence of young infants preferring to look at stimuli that are *familiar* to them (e.g., Bremner, Bryant, Mareschal, & Volein, 2007). In line with Thomas et al.'s (2018) findings and interpretations regarding auditory-tactile colocation in infancy, our interpretation of this preference for visual-tactile colocation at

4 months is that it represents a familiarity preference for a perceptual state of affairs which is more typically experienced ecologically than noncolocation. But why exactly should infants' preferences switch from familiarity (colocation) to novelty (noncolocation) between 4 and 6 months of age? Three factors determining familiarity versus novelty preferences are well documented in the infant learning literature. Supported by a range of findings (e.g., Caron & Caron, 1968; Cohen, Gelber, & Lazar, 1971; Hunter, Ross, & Ames, 1982; Rose, Gottfried, Melloy-Carminar & Bridger, 1982; Wetherford & Cohen, 1973), Hunter and Ames (1988) propose a three-factor model of infants preferences for familiar and novel. All three of Hunter and Ames's factors can help to explain a greater preference for familiarity in the 4-month-olds tested in the studies reported here. First, consistent with our familiarity-novelty account, younger infants are more likely to demonstrate a familiarity preference (Hunter & Ames, 1988). Second, a novelty preference is predicted by longer exposure to the familiarized stimulus (e.g. Hunter, Ames & Koopman, 1983; Hunter et al., 1982; Röder, Bushnell, & Sasseville, 2000). If we treat prior experience of visual-tactile colocation as the familiarized stimulus, and assume that exposure to visual-tactile colocation increases with age, this predicts increasing preference for noncolocation with age. Lastly, Hunter and Ames's (1988) model also includes the complexity of the perceptual discriminative task as a factor predicting greater familiarity preference (e.g., Caron & Caron, 1968; Cohen et al., 1971). There is at least one reason to believe that differentiation between colocation and noncolocation would be more complex (and thus more likely to yield a familiarity preference) for the younger age group. To detect visual-tactile colocation, it may be that infants need to take the relative postures of the eyes and arms into account in order to align visual and tactile frames of reference. The sensory abilities required to differentiate the proprioceptive/visual cues necessary for this are likely to be more limited in 4- than 6-month-old infants. Overall then, an account of our findings in terms of a switch between preferences for familiar visual-tactile spatial pairings in younger infants and novel pairings in older infants is consistent with what the literature tells us about the development of familiarity and novelty preferences.

What kind of representations underlies 4- and 6-month-old infants' ability to perceive colocated visual-tactile events? The use of control conditions allowed us to rule out accounts of both 4- and 6-month-olds' visual-tactile spatial ability in terms of

a discrimination on the basis of a supramodal spatial code. Because the infants preferred colocated (or noncolocated) visual-tactile events over colocated (or noncolocated) unisensory events, we can conclude that their preferences are based on differentiation in terms of their bimodal spatial relations between tactile and visual stimuli, rather than spatial relations among stimuli, irrespective of the perceptual modalities which they belong to. However, further questions remain about the nature of the crossmodal perceptual phenomena which infants experience and there are important limitations in the conclusions which we can draw from our findings, which we next discuss.

Importantly, it remains unclear whether or not the infants tested in our experiments bound the visual and tactile stimuli into a single perceptual event or perceived it as having a common causal origins (see Körding et al., 2007; Rohe & Noppeney, 2015; Spence & Bayne, 2015). In adults, temporal synchrony and (in some circumstances; see Spence, 2013) spatially colocated stimuli result in the perception of a multisensory event with a single origin. On the basis of the current data, it is possible that the infants' sensitivity to visual-tactile colocation was based on either a perception of separate colocated visual and tactile stimuli or a single integrated visual-tactile stimulus. Interestingly, research across a range of multisensory situations has suggested that such integration may not develop until around 8 months of age (Neil, Chee-Ruiter, Scheier, Lewkowicz, & Shimojo, 2006), or even later (Barutchu, Crewther, & Crewther, 2009; Burr, Binda, & Gori; 2013; Gori, Del Viva, Sandini, & Burr, 2008; Nardini, Begus, & Mareschal, 2013; Nardini, Jones, Bedford, & Braddick, 2008). Important questions for future research therefore include addressing the extent to which perceived synchrony and spatial colocation between visual and tactile stimuli affect infants' perception of unified multisensory events, and whether these constraints on multisensory integration change across early life.

An ability to perceive one's own body and the relationships between it and the external world is underpinned by multisensory processes in which tactile cues from the limbs and skin are combined with causally related information in the other senses (particularly audition and vision; Bremner, 2017; Körding et al., 2007; Rohe & Noppeney, 2015). As a piece in the puzzle of how these abilities emerge, the results from the studies reported here have shown that infants aged 4 and 6 months are sensitive to whether or not visual and tactile stimuli presented at the same time occurred on either the same or different feet.

The 6-month-olds (Experiment 1) demonstrated a novelty preference for when the stimuli was separated in space, whereas the 4-month-olds (Experiments 1 and 2) showed a familiarity preference when the stimuli shared spatial coordinates. These studies are the first to establish that, from at least 4 months of age, infants are able to locate visual and tactile stimuli, on the body. Despite this early ability to colocate vision and touch on the body, we think it likely that such abilities are heavily underpinned by visual-tactile experience in the first months of life. However, given that the first successful visually targeted reaches do not generally occur until 5 months of age, our findings show that the visual-tactile experiences which infants have received by the time they are skilled at reaching with the hands are not a necessary sensorimotor prerequisite for learning about visual-tactile space.

## References

Azañón, E., Camacho, K., Morales, M., & Longo, M. R. (2018). The sensitive period for tactile remapping does not include early infancy. *Child Development*, 89, 1394–1404. https://doi.org/10.1111/cdev.12813

Bahrick, L. E., & Lickliter, R. (2000). Intersensory redundancy guides attentional selectivity and perceptual learning in infancy. *Developmental Psychology*, 36(2), 190.

Bahrick, L. E., & Lickliter, R. (2012). The role of intersensory redundancy in early perceptual, cognitive, and social development. In A. J. Bremner, D. J. Lewkowicz, & C. Spence (Eds.), *Multisensory development* (pp. 183–206). Oxford, UK: Oxford University Press.

Bahrick, L. E., & Watson, J. S. (1985). Detection of intermodal proprioceptive–visual contingency as a potential basis of self-perception in infancy. *Developmental Psychology*, 21, 963–973. https://doi.org/10.1037/0012-1649.21.6.963

Begum Ali, J., Cowie, D., & Bremner, A. J. (2014). Effects of posture on tactile localization by 4 years of age are modulated by sight of the hands: Evidence for an early acquired external spatial frame of reference for touch. *Developmental Science*, 17, 935–943. https://doi.org/10.1111/desc.12184

Begum Ali J., Spence C., Bremner A. J. (2015). Human infants' ability to perceive touch in external space develops postnatally. *Current Biology*, 25, (20), R978–R979. https://doi.org/10.1016/j.cub.2015.08.055

Barutchu, A., Crewther, D. P., & Crewther, S. G. (2009). The race that precedes coactivation: Development of multisensory facilitation in children. *Developmental Science*, 12(3), 464–473.

Bremner, A. J. (2017). The origins of body representations in early life. In A. Alsmith & F. De Vignemont (Eds.), *The body and the self, revisited* (pp. 3–31). Cambridge, MA: MIT Press.

Bremner, A. J., Bryant, P., Mareschal, D., & Volein, Á. (2007). Recognition of complex object-centred spatial configurations in early infancy. *Visual Cognition*, *15*, 896–926. https://doi.org/10.1080/13506280601029739

Bremner, A. J., Holmes, N. P., & Spence, C. (2008). Infants lost in (peripersonal) space? *Trends in Cognitive Sciences*, *12*, 298–305. https://doi.org/10.1016/j.tics.2008.05.003

Bremner, A. J., Mareschal, D., Lloyd-Fox, S., & Spence, C. (2008). Spatial localization of touch in the first year of life: Early influence of a visual spatial code and the development of remapping across changes in limb position. *Journal of Experimental Psychology: General*, *137*, 149–162. https://doi.org/10.1037/0096-3445.137.1.149

Burr, D., Binda, P., & Gori, M. (2013). Multisensory integration and calibration in adults and in children. In J. Trommershauser, K. Körding, & M. S. Landy (Eds.), *Sensory cue integration* (pp. 173–194). Oxford, UK: Oxford University Press.

Caron, R. F., & Caron, A. J. (1968). The effects of repeated exposure and stimulus complexity on visual fixation in infants. *Psychonomic Science*, *10*, 207–208. https://doi.org/10.3758/BF03331483

Cohen, L. B., Gelber, E. R., & Lazar, M. A. (1971). Infant habituation and generalization to differing degrees of stimulus novelty. *Journal of Experimental Child Psychology*, *11*(3), 379–389. https://doi.org/10.1016/0022-0965(71)90043-9

Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*, 175–191. https://doi.org/10.3758/BF03193146

Filippetti, M. L., Johnson, M. H., Lloyd-Fox, S., Dragovic, D., & Farroni, T. (2013). Body perception in newborns. *Current Biology*, *23*, 2413–2416. https://doi.org/10.1016/j.cub.2013.10.017

Filippetti, M. L., Orioli, G., Johnson, M. H., & Farroni, T. (2015). Newborn body perception: Sensitivity to spatial congruency. *Infancy*, *20*, 455–465. https://doi.org/10.1111/infa.12083

Freier, L., Mason, L., & Bremner, A. J. (2016). Perception of visual-tactile colocation in the first year of life. *Developmental Psychology*, *52*, 2184–2190. https://doi.org/10.1037/dev0000160

Galloway, J. C., & Thelen, E. (2004). Feet first: Object exploration in young infants. *Infant Behavior and Development*, *27*, 107–112. https://doi.org/10.1016/j.infbeh.2003.06.001

Gori, M., Del Viva, M., Sandini, G., & Burr, D. C. (2008). Young children do not integrate visual and haptic form information. *Current Biology*, *18*(9), 694–698.

Holmes, N. P., & Spence, C. (2004). The body schema and multisensory representation(s) of peripersonal space. *Cognitive Processing*, *5*, 94–105. https://doi.org/10.1007/s10339-004-0013-3

Howell, D. C. (1997). *Statistical methods for psychology* (4th ed.). Belmont, CA: Duxbury Press.

Hunter, M. A., & Ames, E. W. (1988). A multifactor model of infant preferences for novel and familiar stimuli. *Advances in Infancy Research*, *5*, 69–95.

Hunter, M. A., Ames, E. W., & Koopman, R. (1983). Effects of stimulus complexity and familiarization time on infant preferences for novel and familiar stimuli. *Developmental Psychology*, *19*, 338–352. https://doi.org/10.1037/0012-1649.19.3.338

Hunter, M. A., Ross, H. S., & Ames, E. W. (1982). Preferences for familiar or novel toys: Effect of familiarization time in 1-year-olds. *Developmental Psychology*, *18*, 519–529. https://doi.org/10.1037/0012-1649.18.4.519

Jaime, M., Bahrick, L., & Lickliter, R. (2010). The critical role of temporal synchrony in the salience of intersensory redundancy during prenatal development. *Infancy*, *15*, 61–82. https://doi.org/10.1111/j.1532-7078.2009.00008.x

Körding, K. P., Beierholm, U., Ma, W. J., Quartz, S., Tenenbaum, J. B., & Shams, L. (2007). Causal inference in multisensory perception. *PLoS One*, *2*, e943. https://doi.org/10.1371/journal.pone.0000943

Lewkowicz, D. J., & Bremner, A. J. (2020). The development of multisensory processes for perceiving the environment and the self. In K. Sathian & V. S. Ramachandran (Eds.), *Multisensory perception: From laboratory to clinic* (pp. 89–112). Cambridge, MA: Academic Press.

Lewkowicz, D. J., & Ghazanfar, A. A. (2009). The emergence of multisensory systems through perceptual narrowing. *Trends in Cognitive Sciences*, *13*, 470–478. https://doi.org/10.1016/j.tics.2009.08.004

Lewkowicz, D. J., Leo, I., & Simion, F. (2010). Intersensory perception at birth: Newborns match nonhuman primate faces and voices. *Infancy*, *15*(1), 46–60. https://doi.org/10.1111/j.1532-7078.2009.00005.x

Ley, P., Bottari, D., Shenoy, B. H., Kekunnaya, R., & Röder, B. (2013). Partial recovery of visual–spatial remapping of touch after restoring vision in a congenitally blind man. *Neuropsychologia*, *51*, 1119–1123. https://doi.org/10.1016/j.neuropsychologia.2013.03.004

Makin, T. R., Holmes, N. P., & Ehrsson, H. H. (2008). On the other hand: Dummy hands and peripersonal space. *Behavioural Brain Research*, *191*(1), 1–10. https://doi.org/10.1016/j.bbr.2008.02.041

Nardini, M., Begus, K., & Mareschal, D. (2013). Multisensory uncertainty reduction for hand localization in children and adults. *Journal of Experimental Psychology: Human Perception and Performance*, *39*(3), 773.

Nardini, M., Jones, P., Bedford, R., & Braddick, O. (2008). Development of cue integration in human navigation. *Current Biology*, *18*(9), 689–693.

Neil, P. A., Chee-Ruiter, C., Scheier, C., Lewkowicz, D. J., & Shimojo, S. (2006). Development of multisensory spatial integration and perception in humans. *Developmental Science*, *9*(5), 454–464.

Pagel, B., Heed, T., & Röder, B. (2009). Change of reference frame for tactile localization during child

development. *Developmental Science*, *12*, 929–937. https://doi.org/10.1111/j.1467-7687.2009.00845.x

Rigato, S., Begum Ali, J., van Velzen, J., & Bremner, A. J. (2014). The neural basis of somatosensory remapping develops in human infancy. *Current Biology*, *24*, 1222–1226. https://doi.org/10.1016/j.cub.2014.04.004

Rochat, P. (1998). Self-perception and action in infancy. *Experimental Brain Research*, *123*, 102–109. https://doi.org/10.1007/s002210050550

Rochat, P., & Morgan, R. (1995). Spatial determinants in the perception of self-produced leg movements in 3-to 5-month-old infants. *Developmental Psychology*, *31*, 626–636. https://doi.org/10.1037/0012-1649.31.4.626

Röder, B. J., Bushnell, E. W., & Sasseville, A. M. (2000). Infants' preferences for familiarity and novelty during the course of visual processing. *Infancy*, *1*, 491–507. https://doi.org/10.1207/S15327078IN0104_9

Röder, B., Rösler, F., & Spence, C. (2004). Early vision impairs tactile perception in the blind. *Current Biology*, *14*, 121–124. https://doi.org/10.1016/j.cub.2003.12.054

Rohe, T., & Noppeney, U. (2015). Cortical hierarchies perform Bayesian causal inference in multisensory perception. *PLoS Biology*, *13*, e1002073. https://doi.org/10.1371/journal.pbio.1002073

Rose, S. A., Gottfried, A. W., Melloy-Carminar, P., & Bridger, W. H. (1982). Familiarity and novelty preferences in infant recognition memory: Implications for information processing. *Developmental Psychology*, *18*, 704–713. https://doi.org/10.1037/0012-1649.18.5.704

Spence, C. (2013). Just how important is spatial coincidence to multisensory integration? Evaluating the spatial rule. *Annals of the New York Academy of Sciences*, *1296*(1), 31–49.

Spence, C., & Bayne, T., & (2015). Is consciousness multisensory? In D. Stokes, M. Matthen & S. Biggs (Eds.), *Perception and its modalities* (pp. 95–132). Oxford, UK: Oxford University Press.

Thomas, R. L., Misra, R., Akkunt, E., Ho, C., Spence, C., & Bremner, A. J. (2018). Sensitivity to auditory-tactile colocation in early infancy. *Developmental Science*, *21*, e12597. https://doi.org/10.1111/desc.12597

von Hofsten, C. (1984). Developmental changes in the organization of prereaching movements. *Developmental Psychology*, *20*, 378–388. https://doi.org/10.1037/0012-1649.20.3.378

Wetherford, M. J., & Cohen, L. B. (1973). Developmental changes in infant visual preferences for novelty and familiarity. *Child Development*, *44*(3), 416–424. https://doi.org/10.2307/1127994

White, B. L., Castle, P., & Held, R. (1964). Observations on the development of visually-directed reaching. *Child Development*, *35*, 349–364. https://doi.org/10.2307/1126701

Zmyj, N., Jank, J., Schütz-Bosbach, S., & Daum, M. M. (2011). Detection of visual–tactile contingency in the first year after birth. *Cognition*, *120*(1), 82–89. https://doi.org/10.1016/j.cognition.2011.03.001