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Two- to eight-month-old infants' perception of dynamic auditory-visual spatial co-location.

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Abstract

From birth, infants can learn associations between the location of static visual objects and the sounds they emit, but there is limited evidence regarding their sensitivity to the dynamic equivalent when a sound-emitting object moves. In four experiments, we investigated 2- to 8-month-olds' ability to process this form of spatial co-location. Whereas there was no evidence of spontaneous sensitivity, all age groups learned a dynamic co-location during habituation, looking longer at test trials in which sound and sight were dislocated. Only 2-month-olds learned the dislocation relation, although 8-month-olds did so following habituation beyond normal criterion. These results are discussed in relation to the intersensory redundancy hypothesis and work in other domains suggesting growing specificity in learning processes with age.

Two- to eight-month-old infants' perception of dynamic auditory-visual spatial co-location

Our experience of the world is based largely on multi-sensory information. For instance, when we manipulate objects we typically see and touch them simultaneously. Also, the sight of a person and the sound of his or her voice are co-located in space, something that also applies to sound-emitting objects in general. Further, when someone speaks, speech sounds correlate in an orderly way with facial movements. When objects or people move they typically produce a sound accompanying their movement and sound is produced when, for instance, a ball bounces on a surface or rolls across a hard floor. The ability to detect the matches and correlations existing in information from separate senses is thus a necessary condition for an integrated multisensory awareness of the world, and vital questions arise regarding the developmental origins of this ability.

Most early accounts of the development of intermodal perception concluded that detection of intersensory equivalence was possible only after the construction of inter-sensory links drawn from experience in the world. Piaget (1952), for instance, identified the need for coordination of separate schemes for looking, hearing, and touching as preconditions for intersensory awareness of the world. Although Piaget made little explicit reference to sensory systems (as opposed to sensori-motor schemes) his account is widely interpreted as implying that infants begin postnatal life experiencing unrelated sensations from each sensory modality.

Despite such accounts, there is long established evidence for some form of intersensory perception early in life. For instance, over 30 years ago it was demonstrated that young infants increase visual activity in the presence of a sound (Horowitz, 1974) and that even newborns tend to look in the direction of a sound (Butterworth & Castillo, 1976). Such findings are predictable on the basis of the theory of perceptual development presented by E.J. Gibson (1969), according to which perception is largely a matter of detecting invariants in perceptual information. This principle has powerful implications for inter-sensory perception, because invariants are higher-order structural features that have generality across modalities. Thus, detection of inter-modal equivalence is just another case of detecting a perceptual invariant. And because detection of invariants is a basic property of perceptual systems, in principle it is possible that inter-modal equivalence is detected from birth.

Over the past 30 years or so, an extensive body of work on infants' intermodal perception has accumulated, largely stimulated by this theoretical viewpoint, and largely focusing on links between auditory and visual information. Until relatively recently, most of the auditory-visual work has focused on infants of 4 months or older. One productive technique involves presenting two dynamic events side by side accompanied by a sound-track that matches one but not the other. For instance, Spelke (1979) presented two bouncing ball events, and successively played the sound track (the bounce sound) corresponding to one then the other. Four-month-olds looked longer at the event that coincided with the sound whether this be in terms of the common frequency of the sight and sound, or the co-occurrence of sound and visual impact. Spelke (1981) went on to demonstrate that 4-month-olds could use auditory-visual synchrony to learn to associate specific objects with specific sounds.

Auditory-visual spatial co-location refers to cross-modal association between the location of a sound and a visual event and, of course, depends on infants being able to localise sounds. Here there is some disagreement in the literature, with some work indicating a discontinuity or U-shaped developmental function, with auditory localisation hard to elicit at around 2 months (Clifton, Morrongiello, Kulig, & Dowd, 1981; Field, Muir, Pilon, Sinclair, & Dodwell, 1980; Muir, Clifton, & Clarkson, 1989), and other work suggesting a more or less linear increase in localisation ability with age (Morrongiello, 1988; Morrongiello, Fenwick, & Chance, 1990). It appears likely that this disagreement relates to differences in the dependent measure. When visual orienting to sound is measured there is a dip in responsiveness at 2 months that may reflect a change over in the neural system mediating the orienting response (Muir et al., 1989). However, a linear increase in localisation ability emerges when the response to sound position change does not involve orienting to it. This conclusion is in line with evidence from the spatial co-location literature, which suggests this ability is present at birth (Morrongiello, Fenwick, & Chance, 1998) and in older infants, including 2-month-olds (Morrongiello, Fenwick, & Nutley, 1998). We should note, however, that even at 6 to 7 months, accuracy of auditory localisation discrimination is approximately one tenth of adult resolution (Ashmead, Clifton, & Perris, 1987).

Spatial co-location is fundamental to everyday perception and so extending our knowledge of the conditions under which infants reveal sensitivity to auditory-visual spatial co-location should be a priority. A current view is that temporal synchrony between sound and sight is initially more salient than spatial co-location (Morrongiello, et al., 1998). However, spatial co-location is also a ubiquitous feature of intersensory information from the world; there are frequent cases in which objects produce sound that are consistently co-located with their visual manifestation. Examples include people, who frequently talk while stationary or in motion and generally produce some sound of footfall when in motion, mechanical mobile toys within the home, and many forms of mechanised transport in the wider environment.

A feature of many studies of spatial co-location (e.g. Fenwick & Morrongiello, 1998; Morrongiello et al., 1998) is that they involve events at two fixed places: although the events themselves may be dynamic (for instance, the visual stimulus may move up and down to gain and maintain the infant's attention), co-location of sound and sight occurs at static locations. However, there is some work that investigates detection of dynamic auditory-visual correspondences for movements in the near-far plane (Pickens, 1994; Walker-Andrews & Lennon, 1985). These studies indicate an ability to form such correspondences at 4 to 5 months. In these cases, however, the correspondence is not a direct spatial one, because auditory 'distance' is specified by sound intensity. Also, Pickens demonstrated that infants showed an association between changing sound amplitude and changing size of the visual stimulus in the absence of cues for movement in depth. This could mean that synaesthetic correspondence between visual size and sound amplitude explains part of the effect in these cases, a possibility made more plausible by evidence for synaesthetic correspondences at 4 months (Walker, Bremner, Mattock, Mason, Spring, Slater, & Johnson, in press) as well as in toddlers (Maurer, Pathman, & Mondloch, 2006; Mondloch & Maurer, 2004).

It thus appears important to investigate dynamic auditory-visual co-location where visual and auditory locations are more directly specified. In this respect, lateral movement is a good candidate for investigation, because it is possible to provide veridical auditory information for changing location. Also there is evidence that infants are sensitive to a *bounce illusion* in which two objects that move smoothly through each other appear to bounce when a sound co-occurs with their fusion (Scheier, Lewkowicz, & Shimojo, 2003), which suggests that intermodal information is likely to be processed in the case of lateral movements. Surprisingly, however, to our knowledge there is no work that investigates dynamic co-location in lateral movements, though this should be relatively easy to investigate. Suppose, for example, infants are habituated to an event sequence in which a sounding object moves back and forth on a horizontal path. It is then possible to test for dishabituation when the object moves as usual but the sound is dislocated, so that, for instance, as the object moves left the sound moves right. If infants show recovery of looking, we can conclude that they have detected the invariant dynamic relation between locus of sight and sound, and note when this is violated. In addition to filling an important gap in the literature, studies of this sort carry the dual advantage of tapping into dynamic events that typically occur in the world (moving objects typically make a sound due to their movement) and of allowing investigation of infants' sensitivity to intermodal factors such as movement rate and phase.

It is not clear what one would predict regarding emergence of this dynamic form of spatial co-location. On the one hand, we might expect quite young infants to reveal this ability. We know that newborns detect spatial co-location in the case of static positions (Morrongiello et al., 1998), and presentation of dynamic information might, if anything, enhance this ability. On the other hand, adults are quite poor at detecting departure from dynamic spatio-temporal co-location of a moving object and a moving sound, there being a tendency to perceive a sound as moving with the visual object even when it is not (Soto-Faraco, Kingstone, Lyons, Gazzaniga, & Spence, 2002). If this tendency exists in infants it could act as a barrier to detection of dislocation between sight and sound.

The work reported here is a systematic investigation of circumstances under which infants detect violation of amodal auditory-visual relations in dynamic events involving sounding objects. We employ well-tested techniques used successfully to investigate object unity (Johnson, Bremner, Slater, & Mason, 2000) and trajectory perception (Bremner et al., 2005; 2007) in infancy, and report four experiments that investigate the conditions under which infants detect changes in spatio-temporal co-location and dislocation between moving visual and auditory stimuli. In all four experiments, as the visual stimulus we use an image of a ball, moving on a horizontal trajectory, and as the auditory stimulus we use an attractive sound, stereophonically produced so as to create the impression (to adults) that it moved with or in the opposite direction to the object. Thus in co-located displays there was amodal dynamic co-location of sound and sight, but the relation between the nature of the sound and the nature of the object was arbitrary. The latter choice was made partly because piloting indicated that it was important to ensure that both the auditory and visual stimulus were salient, and more 'realistic' sounds, such as that of a ball rolling, did not appear to recruit attention. Additionally, however, many of the sound-emitting physical objects that infants encounter produce sounds that are arbitrarily related to their visual appearance; this is particularly true of infant toys. Thus, for both methodological and theoretical reasons we chose a sound that was completely arbitrary relative to the visual object.

Dynamic auditory-visual spatial co-location is an amodal intersensory relation involving redundant presentation of information across the senses, and there is good evidence that redundant presentation of this sort recruits infants' attention and enhances learning (Bahrick, Flom, & Lickliter, 2002; Bahrick & Lickliter, 2000; Bahrick, Lickliter, & Flom, 2004), It should be noted that in all displays used in this series, there was also temporal redundancy consisting of the common onset and offset, and hence duration of visual and auditory events. However, although stimulus onset generally happened when infants were fixating the screen, offset generally occurred when infants were looking away. Also, there were no discontinuities in auditory and visual stimuli during trials. Thus, only common onset information was liable to be consistently perceived by infants. However, given of the argument that temporal synchrony is initially more salient than spatial co-location (Morrongiello et al., 1998), it is possible that common onset is salient enough to cue that sound and sight are linked. Thus, this information in itself may be sufficient to link auditory and visual information that is spatially dislocated. Thus, in some of our experiments we investigate infants' ability to learn a dislocated relationship between sight and sound in which the sound appears to move in the opposite direction to the visual object.

Experiment 1

Many experiments on cross-modal perception obtain clear effects with no prior habituation, and it is possible that dynamic spatial co-location is so salient that infants would detect its violation immediately with no prior familiarisation with or learning of the event. In other words, if we present infants with a series of test trials, half in which the sound and object move in co-location and half in which they move in dislocation, a strong predisposition towards co-location might be revealed in longer looking at one or other of the test trials. It is not clear which test trial we would expect to attract longer looking. On the one hand, work on detection of temporal synchrony demonstrates that infants look longer at the visual display that is in synchrony with the soundtrack (Spelke, 1981), which would lead us to expect that infants would look longer at the co-located test trials. On the other hand, the literature on core knowledge in infancy (reviewed in Spelke & Kinzler, 2007) provides numerous examples of infants' tendency to look longer at events that violate their expections. If departure from dynamic auditory-visual spatial co-location is perceived as a violation of normal reality, it is possible that infants would look longer at the display that violated their expectation. The important point is that a clear result in either direction would be informative, indicating sensitivity to dynamic co-location. Thus, in our first experiment, we measured infants' visual attention on four test trials, two of which presented sound and sight moving in co-location, and two of which presented sound and sight moving in dislocation.

Method

Participants. Thirty-six infants took part, 12 2-month-olds (*M* = 62.92 days; range 54 – 71 days; 5 girls and 7 boys), 12 5-month-olds (*M* = 156.8 days; range 140 – 167 days; 6 girls and 6 boys), and 12 8-month-olds (*M* = 243.8 days; range 233 – 262 days; 6 girls and 6 boys). A further 6 infants were not included due to fussiness (2 2-month-olds and 3 8-month-olds) or technical problems (1 8-month-old). In all experiments, participants were recruited by personal contact with parents in the maternity unit when the baby was born, followed up by telephone contact near test age to those parents who volunteered to take part. Infants with reported health problems including visual and hearing deficits and those born two weeks or more before due date were omitted from the sample. The majority were from Caucasian, middle class families.

Apparatus. The room in which testing took place was partitioned with black curtaining, creating a cubicle measuring 3 metres square. In this way, the experimenter and the equipment, other than a plasma screen and camera, were out of view of the infant. The plasma screen created one of the 'walls' of the cubicle, and was blanked off to leave a visible screen 135cm wide by 17cm high, with the mid-point on the vertical dimension approximately at the infant's eye level. A Macintosh G4 computer and the plasma screen were used to present stimuli and collect looking time data. A JVC, low-light, black and white camera was sited above the plasma screen, and was connected to a monitor that the observer used to record looking times. The observer's judgments were input with a key press on the computer keyboard. Infants were recorded on videotape for later independent coding for inter-observer reliability measurement. The computer presented displays and recorded looking time judgments. Order and length of display presentation was managed using HABIT software (Cohen, Atkinson, & Chaput, 2004).

Stimuli. Animations were created using InfiniD software and Sound Edit files. The finished movies showed a (green) ball (6.7cm) going back and forth at a speed of 18 cm/sec across the screen (see Figure 1). The sound was presented stereophonically via two hidden speakers mounted at the ends of the visual display, creating the impression of a sound moving at the same speed as the ball. This was achieved through varying the balance from equal volume at each speaker (and hence equal intensity at both ears of the listener) smoothly to two extremes when sound only came from one or the other speaker. Given the placement of the speakers directly at the extremes of visual object motion, and assuming the use of inter-aural intensity difference to locate the sound, this provides objective co-location of visual and auditory information at the mid point and extremes, and the smooth alteration in balance may be assumed to maintain a smooth change between midpoint and extremes. On each trial both the ball and the sound originated at the center of the display and, depending on trial type, moved in the same or opposite directions. A full cycle (for example, center to left to right to center) took 15 seconds. The sound was a complex pulsating tone sequence that had been used in previous research as an attention-getter, so its suitability to attract and sustain attention had been verified. The object and sound cycled continuously with no breaks or static components for the duration of each trial. Background texture for the animations was provided by a light blue cloudy diffuse image that covered the entire visible screen.

Procedure. Infants were given time to adjust to their new surroundings and during this time an explanation of the procedure was given to the parent and informed consent obtained. The parent was asked to sit, with the baby on his or her lap, on an adjustable wheeled office chair that could be positioned easily and accurately so that the infant was one meter from the plasma screen. The parent was asked to remain quiet throughout and to look either at the screen or at the top of the infant's head. Given that, when questioned, most parents were unaware that the relationship between sound and visual object varied across test trials, it is unlikely that they influenced infants' looking. Testing took place with the main room lights off.

Following initial acclimatisation, four test trial animations were presented in two blocks each consisting of a co-located event in which object and sound appeared to move together, and a dislocated event in which the sound and object travelled in the opposite directions. Thus, co-located and dislocated trials were presented in alternation. Order of presentation was counterbalanced. Prior to each trial, an attention-getter visual stimulus was presented to ensure infant fixation, and the test trial commenced as soon as fixation was achieved. Each trial continued either until 60 seconds had elapsed or the infant had looked away for 2 seconds.

A second observer used the recordings of infant gaze to second score the looking times for reliability purposes. The mean correlation between the scores of the two observers was .988 (SD = .018). Neither observer was aware of the hypothesis under investigation, or the display being presented at any point in the session. Although the primary observer could hear the sound, localisation was not possible due to the physical barriers presented by the equipment and screening.

Results

Preliminary analyses revealed no reliable main effects or interactions concerning sex of participants, so data were collapsed across this variable in all experiments. Looking time data in many cells were positively skewed, violating assumptions of homogeneity of variance required by ANOVA; therefore scores were log-transformed prior to analysis in all the experiments (data in the figures are based on raw scores). ANOVAs based on raw scores revealed broadly the same patterns of significance. Figure 2 shows looking times to co-located versus dislocated test trials subdivided by age group and trial block. In all but the 8-month-olds' second trial block there was a small preference for the dislocated test display. However, this was not a reliable effect, because a 3 (age group) x 2 (test trial order) x 2 (co-location: co-located vs. dislocated) x 2 (test trial block) mixed ANOVA revealed neither a significant effect of co-location, $F\ (1, 30) = .33$, $p = .7$, $\eta_p^2 = .005$, nor a significant interaction between co-location and age, $F\ (2, 30) = .19$, $p = .83$, $\eta_p^2 = .01$. The only effect to reach significance was trial block, $F\ (1, 30) = 11.47$, $p = .002$, $\eta_p^2 = .28$, due to a general reduction in looking across trial blocks.

The lack of an effect of co-location was confirmed by the fact that 6/12 2- and 5-month-olds (*binomial* $p = .61$), and 7/12 8-month-olds (*binomial* $p = .39$) looked longer overall at the dislocated test display.

Discussion

No evidence emerged in any age group of an affect of violation of dynamic spatial co-location in a version of the task that did not involve prior habituation to a co-located dynamic event. This could mean either that infants were incapable of processing departures from dynamic auditory-visual spatio-temporal co-location, or that this form of co-location is so immediately salient that infants respond spontaneously to its violation. The lack of a trial effect cannot be attributed to a ceiling effect, because although looking times were relatively high, they were below ceiling, particularly on the second trial block.

Experiment 2

The possibility that it takes some time to learn about dynamic spatial co-location is very much in keeping with current theory of intersensory perception. According to the intersensory redundancy hypothesis (Bahrick, Flom, & Lickliter, 2002; Bahrick & Lickliter, 2000; Bahrick, Lickliter, & Flom, 2004), early in development, attention to and detection of amodal properties is enhanced when these properties are presented redundantly across two or more senses, as opposed to when they are presented non-redundantly to one sense. Thus, in the present case this hypothesis would predict that infants are likely to attend selectively to dynamic information for object movement after presentation of a series of trials in which this information is consistently presented redundantly across visual and auditory senses. In contrast, in Experiment 1, although all trials contained multimodal information, two trials provided redundant co-location information and two provided non-redundant information in the sense that auditory and visual information were dislocated.

Consequently, in Experiment 2 we repeated Experiment 1 with the difference that infants were first habituated to the co-located display prior to the same test trials as before, the aim of prior habituation being to ensure that infants were given extensive redundant presentation of information about object movement prior to test trials.

Method

Participants. Thirty-six infants took part, 12 2-month-olds (*M* = 70.75 days; range 55 – 82 days; 5 girls and 7 boys), 12 5-month-olds (*M* = 153.4 days; range 142 – 169 days; 6 girls and 6 boys), and 12 8-month-olds (*M* = 249.4 days; range 235 – 258 days; 6 girls and 6 boys). A further 7 infants were not included due to fussiness (two 2-month-olds and two 8-month-olds), failure to habituate (one 8-month-old), or technical problems (two 8-month-olds). Infants were recruited from the same population and through the same procedures as Experiment 1.

Apparatus, displays, & procedure. The same apparatus and displays were used as in Experiment 1. Prior to test trials, infants were habituated to the co-located test display; otherwise the procedure was identical to that of Experiment 1. Parents were told that part of the process of habituation would involve the baby getting bored, that they should not be concerned if the baby looked away from the screen, and that they should not try to direct the baby's attention towards it. Progress to habituation was recorded through a sliding window measure that summed the looking times over the current and preceding three trials. Subject to a maximum of 12 trials, the habituation display was presented until looking time declined across four consecutive trials, from the second trial on, adding up to less than half the total looking time during the first four trials. Prior to each trial an attention-getting display was presented and as soon as the infant's attention was on the display the trial commenced. A trial was terminated when the infant looked away for two seconds or 120 s had elapsed. The computer presented displays, recorded looking time judgments, calculated the habituation criterion for each infant, and changed displays after the criterion was met. Between trials, a beeping target was shown to attract attention back to the screen. There were two different animations used: one where the ball started in the middle of the screen and moved to the left, the other where the ball started in the middle of the screen and moved to the right. The order of these trials was randomly determined with no more than two the same presented consecutively. Once habituation trials ended, the four test trials followed immediately, with the same administration conditions as in Experiment 1.

Results

Figure 3 shows test display looking times subdivided by age group and trial block. For all ages, this indicates a tendency to look longer at the dislocated (unexpected) test trial, a tendency that is stronger on the second block of trials. A 3 (age group) x 2 (test trial order) x 2 (co-location) x 2 (test trial block) mixed ANOVA yielded a significant main effect of co-location, F (1, 30) = 17.43, p

= .001, η_p^2 = .37. There was also a significant interaction between co-location and test trial block, *F* (1, 30) = 8.5, *p* = .007, η_p^2 = .22. On the first test trial block the effect of co-location was not quite significant, *F* (1,30) = 3.34, *p* = .078, η_p^2 = .1, whereas on the second block it was highly significant, *F* (1,30) = 27.38, *p* = .001, η_p^2 = .48 . This interaction was qualified by a significant four-way interaction between co-location, test trial block, test trial order, and age group, *F* (2, 30) = 5.46, *p* = .009, η_p^2 = .27. To investigate this, further analyses were carried out for each age group separately. In the case of 2-month-olds, there was a significant interaction between co-location, test trial block, and test trial order, *F* (1, 10) = 7.88, *p* = .019, η_p^2 = .44. Further analysis indicated that on the first test trial block there was a significant interaction between co-location and test trial order, *F* (1, 10) = 6.62, *p* =. 027, η_p^2 = .4, that arose from infants looking longer at the test trial presented second, whereas on the second test trial block infants looked significantly longer at the dislocated test display, *F* (1, 10) = 8.52, *p* = .015, η_p^2 = .46. In the case of 5-month-olds, there was a significant effect of co-location, *F* (1, 10) = 14.48, *p* = .003, η_p^2 = .59, qualified by a significant interaction between co-location and test trial block, *F* (1, 10) = 6.44, *p* = .03, η_p^2 = .39. On the first block, the effect of co-location was not significant, *F* (1, 10) = 2.83, *p* = .12, η_p^2 = .22, whereas on the second block it was highly significant, *F* (1, 10) = 43.4, *p* = .001, η_p^2 = .81. In the case of 8-month-olds, there was a significant effect of co-location, *F* (1, 10) = 6.44, *p* = .029, η_p^2 = .39, but the interaction between co-location and test trial block was not significant, *F* (1, 10) = 3.34, *p* = .097, η_p^2 = .25.

The same general pattern emerges from analysis of the number of infants looking longer at the dislocated test display. On the first block of trials, 7/12 2-month-olds (*binomial p* = .39), 8/12 5-month-olds (*p* = .19) and 7/12 8-month-olds looked longer at the dislocated trial, whereas on the second block, 10/12 2-month-olds (*p* = .02), 12/12 5-month-olds (*p* = .001) and 11/12 8-month-olds (*p* = .006) did so.

Finally, a comparison of mean looking times data with Experiment 1 revealed a significant interaction between co-location and experiment, F(1,60) = 9.39, $p = .003$, $\eta_p^2 = .23$, reflecting an effect of co-location in Experiment 2 but not in Experiment 1.

Discussion

By the second block of test trials all age groups showed a significant preference for the dislocated test display, and in the case of the 8-month-olds, this was evident on the first test trial block as well. Thus, it appears that from 2 months infants are capable of learning a dynamic auditory-visual spatial co-location relation during habituation trials and respond to its violation on test trials. For the younger infants, the lack of a significant effect on the first test trial block may be evidence that the effect of violating dynamic co-location is relatively subtle, such that younger infants take some trials to detect it clearly. And there is reason to expect that the effect would be relatively subtle. As indicated in the introduction, adults are subject to a tendency to perceive a sound as moving with the visual object even when it is not (Soto-Faraco et al., 2002), and although the same effect has not been investigated in infants, 5-month-olds are subject to visual dominance in syllable detection (the McGurk effect), in some cases giving priority to visual information in perceiving the syllable presented (Rosenblum, Schmuckler, & Johnson, 1997). Thus, it is possible that infants are subject to the same effect as adults, though only to the extent of partially suppressing sensitivity to auditory-visual dislocation.

Experiment 3

In contrast to the null results obtained in Experiment 1, infants who were first habituated to the co-located display, and who thus had repeated experience of redundant presentation of information about object movement, showed sensitivity to violation of auditory-visual matching of this information (dynamic spatial co-location). According to the intersensory redundancy hypothesis, redundant presentation of information enhances attention to the stimulus property concerned, and on this basis we would expect this form of presentation during habituation trials would be conducive to learning and auditory visual relation. However, it is possible that the more restricted redundant information presented by common onset is sufficient to support learning even if location information is presented non-redundantly between the senses. If this is the case, infants may reveal similar effects when the task is 'run backwards'. Specifically, following habituation to the dislocated display, infants may show a looking preference for the co-located display, the opposite result from that obtained in Experiment 2. Although this form of habituation seems likely to present unfavourable conditions for learning, the change from non-redundant to redundant presentation of location information on colocated tests trials may in itself cue attention. Thus, in Experiment 3 we repeated Experiment 2 with the difference that, prior to test trials, infants were first habituated to the dislocated display.

Method

Participants. Thirty-six infants took part, 12 2-month-olds (*M* = 62.2 days; range 56 – 67 days; 5 girls and 7 boys), 12 5-month-olds (*M* = 159.6 days; range 142 – 167 days; 7 girls and 5 boys), and 12 8-month-olds (*M* = 246.8 days; range 239 – 253 days; 5 girls and 7 boys). A further 8 infants (four 2-month-olds, two 5-month-olds and two 8-month-olds) were not included due to fussiness. Infants were recruited from the same population and through the same procedures as in previous excperiments.

Apparatus, displays, & procedure. The same apparatus and displays were used as in Experiments 1 and 2. The same procedure was followed as in Experiment 2, except that infants were habituated to the dislocated display rather than the co-located display prior to test trials.

Results

Figure 4 shows test display looking times subdivided by age group and trial block. Although there is a preference for the co-located test trial at 2 and 5 months it is very small at 5 months and the 8-month-olds show a slight preference in the opposite direction. A 3 (age group) x 2 (test trial order) x 2 (co-location) x 2 (test trial block) mixed ANOVA revealed neither a significant effect of co-location, F (1, 30) = 2.14, p = .154, η_p^2 = .15, nor a significant interaction between co-location and age group, F (2, 30) = 1.47, p = .247, η_p^2 = .09. There was a significant effect of age group, F (2, 30) = 6.09, p = .006, η_p^2 = .29, 2-month-olds looking significantly longer than 5-month-olds, Newman-Keuls p = 005, and 8-month-olds, Newman-Keuls p = .02. There was also a significant interaction between test trial order and age group, F (2, 30) = 4.57, p = .018, η_p^2 = .234, qualified by a significant interaction between co-location, test trial block, test trial order, and age group, F (2, 30) = 4.66, p = .017, η_p^2 = .237. Further investigation indicated that these effects were explained by the 8-month-olds' data, which revealed a significant effect of test trial order, F (1, 10) = 6.25, p = .031, η_p^2 = .38, qualified by a significant interaction between co-location, test trial block and test trial order, F (1, 10) = 6.04, p = .034, η_p^2 = .38. The effect of test trial order was due to longer looking at both test trials when the dislocated trial was presented first, and the interaction reflects the fact that the exception to this is the first dislocated test trial, for which looking is unaffected by test trial order. There is no clear explanation for either of these effects. No significant main effects or interactions involving these factors were obtained in other age groups.

The lack of an effect of co-location is confirmed by the fact that 8/12 2-month-olds and 5-month-olds (*binomial* p = .19) and 7/12 8-month-olds (p = .39) looked longer overall at the co-located test display. However, 2-month-olds showed longer looking to the co-located test trial on both blocks and the magnitude of this difference was not much less than the opposite effect in experiment 2 for this age group. Although at 2 months the effect of co-location was not significant, F (1,10) = 2.73, p = .13, η_p^2 = .21, closer inspection of the individual data revealed that two 2-month-olds showed extremely long looking times during habituation and went on to look longer at the dislocated test trials. Thus we replicated the experiment with a new group of 2-month-olds (*N = 12, M* 65.1 days , range 54-74 days). An additional 4 infants did not complete testing, 2 due to fussiness and 2 due to sleepiness. The results are displayed in Figure 4. This time, there was substantially longer looking at the co-location test trial and analysis yielded a significant effect of co-location, F(1,10) = 24.4, p = 001, $\eta_p^2 =$ .71, and no other significant effects or interactions.

Discussion

The replication with 2-month-olds yielded a positive result, this age group showing a novelty preference for dynamic co-location following exposure to dynamic dislocation. In contrast, there was no evidence of such an effect at 5 or 8 months. Because there was auditory-visual dislocation during habituation, the only redundant information likely to have been detected was common onset, and presentation of movement information was explicitly non-redundant in presenting different information to the two senses. Thus, given evidence that infants do not learn relations when information is non-redundant at one level (Bahrick, 1998), these trials should have constituted unfavourable conditions for intersensory learning. The result for 2-month-olds is striking and suggests the presence of an early learning ability that functions even when the level of redundancy across the senses is low. As already noted, however, longer looking to co-located test trials following dislocated habituation may simply indicate that infants have detected the shift from non-redundant to redundant presentation of auditory and visual information. The lack of an effect with older infants, in contrast, suggests a developmental progression akin to that detected in other domains such as perception of speech sounds (Werker & Tees, 1984) and, later in infancy, perception of animacy (Rakison & Poulin-Dubois, 2001), form-function relations (Madole & Cohen, 1995), and symbolic reference (Namy & Waxman, 1998), in which an initial general ability becomes increasingly constrained through experience. In this case, we may suppose that infants' accumulating experience of events in which auditory-visual spatial co-location is the rule, leads to increasing difficulty in learning associations that do not involve co-location.

Our final question is whether older infants are simply unable to learn an association involving consistent spatial 'dislocation' and thus do not detect a subsequent shift to co-location. This could be the case because they are unable to learn the auditory-visual association between two dynamic stimuli in the absence of spatial co-location. Alternatively, it may just be harder for older infants to learn the object-sound association when an unfamiliar 'dislocation' relation obtains. Accumulated experience of co-location in older infants may result in a greater sensitivity to co-location and reduced sensitivity to dislocation relations. Thus, in Experiment 4, we repeated Experiment 3 with 5- and 8-month-olds, providing more habituation experience.

Experiment 4

Participants. Twenty-four infants took part, 12 5-month-olds (*M* = 152.8 days; range 141 – 168 days; 6 girls and 6 boys), and 12 8-month-olds (*M* = 250.7 days; range 241 – 261 days; 5 girls and 7 boys). A further 3 infants (one 5-month-old and two 8-month-olds) were not included due to fussiness. Infants were recruited from the same population and through the same procedures as in previous experiments.

Apparatus, displays, & procedure. The same apparatus and displays were used as in Experiments 1 to 3. The same procedure was followed as in Experiment 3, with the exception of a modification in the habituation procedure to ensure fuller habituation. In contrast to the sliding window method used in Experiments 2 and 3 in which the total of four trials was computed for every block of four from trial 2 to 5 onwards, infants were habituated according to a fixed window method in which the total was only sampled across trials 5 to 8, and if the criterion was not met, over trials 9 to 12. As previously, this total was compared to the total looking time across the first four trials, and the habituation criterion was met when total looking across a block of four trials fell to half the total across the first four trials. This meant that, in contrast to the sliding window criterion in which habituation is possible from trial 5 onwards, habituation trials could end only after 8 or 12 trials.

Results

First, to check that infants in Experiment 4 did indeed undergo lengthier habituation than 5- and 8-month-olds in Experiment 3, we compared number of habituation trials and accumulated habituation times between the two experiments. In the case of number of habituation trials, a 2 (experiment) x 2 (age group) ANOVA yielded a significant main effect of experiment, F (1, 44) = 19.12, p = .001, $\eta_p^2 = .3$, with more trials to habituate in Experiment 4 than in Experiment 3, M = 10.00 (SD = 2.04) vs. M = 7.41 (SD = 2.22). There was also a significant main effect of age group, F (1, 44) = 4.48, p = .04, $\eta_p = .09$, 8-month-olds having more habituation trials than 5-month-olds, M = 9.33 (SD = 2.78) vs. M = 8.08 (SD = 2.02). The interaction between experiment and age group was not significant, F (1,44) = 1.61, p = .21, $\eta_p^2 = .03$. In the case of habituation time, a 2 (experiment) x 2 (age group) ANOVA yielded a significant main effect of experiment, F (1, 44) = 4.29, p = .044, $\eta_p^2 = .09$, habituation times being longer in Experiment 4 than in Experiment 3, M = 229.24 s (SD = 147.58) vs. M = 160.59 s (SD = 72.79). There was no significant effect of age group, F(1, 44) = 1.26, p = .27, $\eta_p^2 = .03$, or significant interaction between experiment and age group, F(1,44) = 1.96, p = .17, $\eta_p^2 = .04$.

Figure 5 shows test display looking times subdivided by age group and trial block. The 5-month-olds showed no consistent pattern across test trial blocks, whereas the 8-month-olds showed a looking preference for the co-located test trials on both blocks. A 2 (age group) x 2 (test trial order) x 2 (co-location) x 2 (test trial block) mixed ANOVA revealed a significant effect of co-location, F (1, 20) = 7.15, p = .017, η_p^2 = .31, qualified by a significant interaction between co-location and age group, F (1, 20) = 6.61, p = .02, η_p^2 = .29. Although 5-month-olds showed no looking preference for either test trial, *F* (1, 10) = .01, *p* = .93, $\eta_p^2 = .001$, 8-month-olds showed a significant looking preference for the co-located test display, *F* = (1,10) = 9.48, *p* = .015, $\eta_p^2 = .54$.

This age related pattern is confirmed by the fact that 6/12 5-month-olds (*p* = .61) and 10/12 8-month-olds (*p* = .02) showed an overall looking preference for the co-located test display.

Discussion

Although providing more habituation experience had no effect on 5-month-olds' performance, it led to a significant effect for 8-month-olds, indicating that with additional experience of an event that violated dynamic spatial co-location, this age group showed the reverse of the effect obtained in Experiment 2. Thus, 8-month-olds were able to learn a 'dislocation' relation, and detect when it changes to a co-location relation. The fact that in both experiments 3 and 4, 8-month-olds took more trials to habituate than 5-month-olds may reflect their attempts to engage with this dislocation. It is very possible that learning this relation occurs through learning that sound and object are related due to their common onset, detecting the spatial dislocation relation and detecting when it changes to co-location.

General Discussion

The main aim of this series of studies was to establish the conditions under which infants are capable of detecting dynamic auditory-visual spatial co-location and responding to events in which co-location is abolished. In Experiment 1, in which no habituation trials were administered prior to test, infants showed no differences in looking at co-located and dislocated test trials, suggesting that in none of the age groups tested was there what might be described as a spontaneous expectation that sight and sound should move together. It is possible, however, that dynamic spatial co-location is rather too subtle to be picked up immediately; the fact that few adults noted the change from collocated to dislocated trials is in keeping with this. However, in Experiment 2, following habituation to the co-located event, infants at all ages showed a looking preference for the dislocated test event, though for the younger groups this was only firmly established by the second block of test trials. This is clear indication that, from as early as 2 months of age, infants are capable of detecting the dynamic association between a horizontally moving object and a similarly moving sound. To our knowledge, this is the first demonstration of this ability, other than in cases of movements in the depth plane in which sound position was represented by sound amplitude. Unlike the case of sound amplitude, which varies for a number of reasons other than sound distance, and which may bear a synaesthetic relationship to visual stimulus properties (Walker et al., in press), stereophonic presentation of sound in the horizontal plane is unambiguous information about sound location.

Although this work demonstrates that even very young infants are capable of processing dynamic information for spatial co-location the work is silent regarding the processes underlying this ability. In principle it is possible that infants sample instances from the display and detect co-location or dislocation in these 'snapshots'. However, it must be noted that neither the auditory nor the visual stimulus was ever static. Additionally, such a process is very much the antithesis of arguments emerging from ecological theory regarding the dynamic nature of perception (Gibson, 1979), and it seems likely that we are tapping into a truly dynamic process.

In Experiment 3, following habituation to the dislocated event, only 2-month-olds looked longer at the co-located test display, although in Experiment 4, following more thorough habituation to the dislocated event, 8-month-olds (but not 5-month-olds) showed a looking preference for the co-located test event. . The outcome with 2-month-olds is striking, and it is not clear that this result would be predicted by the IRH. Spatial dislocation is a more extreme departure from redundant presentation than is used in many tests of the IRH, in which non-redundant presentation generally involves presentation in only one modality. And spatial dislocation may be a particularly difficult association to learn, both because it effectively involves learning a systematic dissociation rather than an association, and because it is an event that does not occur in nature. Also, there is evidence that young infants do not detect changes in rhythm in mechanical events (Bahrick & Lickliter, 2000) and affect in social stimuli (Flom & Bahrick, 2007) when the auditory and visual components are presented out of synchrony. However, it is possible that, rather than learning the dislocation relationship, infants simply note the shift from non-redundant to redundant presentation of location information. In other words, the onset of redundancy cues attention. However, if this was the case, why did 5-month-olds infants not show a similar pattern of response, and 8-month-olds only after fuller exposure to the dislocation event? Our favoured interpretation is that, in common with developmental changes in other domains such as speech perception and perception of animacy, infants' perception becomes selectively attuned to the sorts of events that they encounter in everyday life, and that sensitivity to dislocation relations decreases over time.

On the other hand, the fact that the additional habituation in Experiment 4 was sufficient for 8-month-olds to learn a dislocation relation may be evidence of developing efficiency in perceptual learning that, at this age, begins to counteract experience-based perceptual selectivity . Although dislocation events do not occur in the natural world, infants are bombarded with events in which new arbitrary intersensory relations are encountered. For example, in the case of speech perception, although older infants become insensitive to speech sounds that they are not exposed to, this process is reversible when they are exposed to a new language, and there are advantages to being able to 're-learn' these sounds after relatively short exposure. The same perceptual flexibility that supported 8-month-olds' performance in Experiment 4 is likely to serve them well in processing new intersensory relations. A question remains regarding whether this age group are capable of learning arbitrary relations of this sort without the presence of any sort of redundant inter-sensory information linking the two modalities, or whether their performance was supported by redundant common onset information. Thus, it would be of interest to test this age group under circumstances in which no redundant information is present to link information in the two modalities.

We believe that, taken together, the results of this series of studies add to our understanding of the development of intersensory perception by providing evidence regarding the conditions under which infants are sensitive to dynamic spatial co-location and dislocation. Dynamic spatial co-location is ubiquitous in the natural world, but previous work investigating this phenomenon has focused on the case of movement in depth with auditory 'distance' mediated by sound intensity. In contrast, our work specifies auditory position more directly through stereophonic presentation that translates into inter-aural intensity difference, a primary cue to auditory localization. To an extent, our findings appear to be in keeping with the intersensory redundancy hypothesis and, as such, they complement existing work on other aspects of intersensory perception. However, our finding that 2-month-olds apparently learned the dislocation relationship under circumstances in which older infants did not raises the likelihood that future theorising and research on intersensory perception will need to pay more attention to developmental changes resulting from accumulated experience. Although it is clear that intersensory redundancy is an important factor in infant learning, it is not yet clear the extent to which this importance is influenced by the infants' accumulating encounters with intersensory redundancy in everyday experience.

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Figure captions

Figure 1. The displays. In the *co-located* display (top) the sound is presented stereophonically through two speakers at the extremes of the screen so that it moves with the ball. In the *dislocated* display (bottom) the sound is presented moving in the opposite direction to the ball. In both cases both object and sound commence at the center of the screen.

Figure 2. Mean looking times in Experiment 1 plotted by co-location (co-located vs. dislocated), test trial block, and age. Following Masson and Loftus (2003), error bars in all figures indicate $(MS_{within}/n)^{-2}(t_{critical})$.

Figure 3. Mean looking times in Experiment 2 plotted by co-location (co-located vs. dislocated), test trial block, and age.

Figure 4. Mean looking times in Experiment 3 plotted by co-location (co-located vs. dislocated), test trial block, and age.

Figure 5. Mean looking times in Experiment 4 plotted by co-location (co-located vs. dislocated), test trial block, and age.

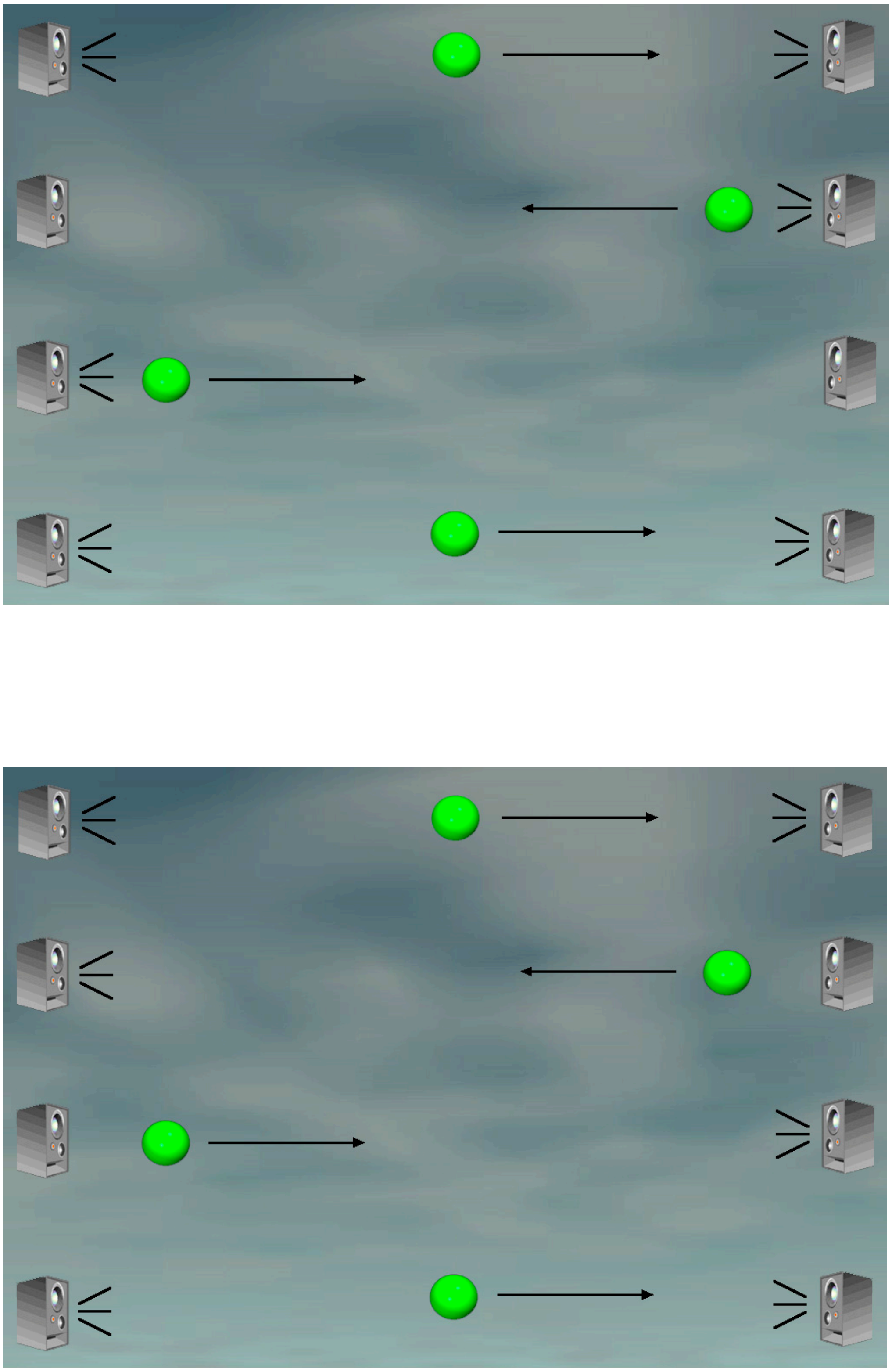
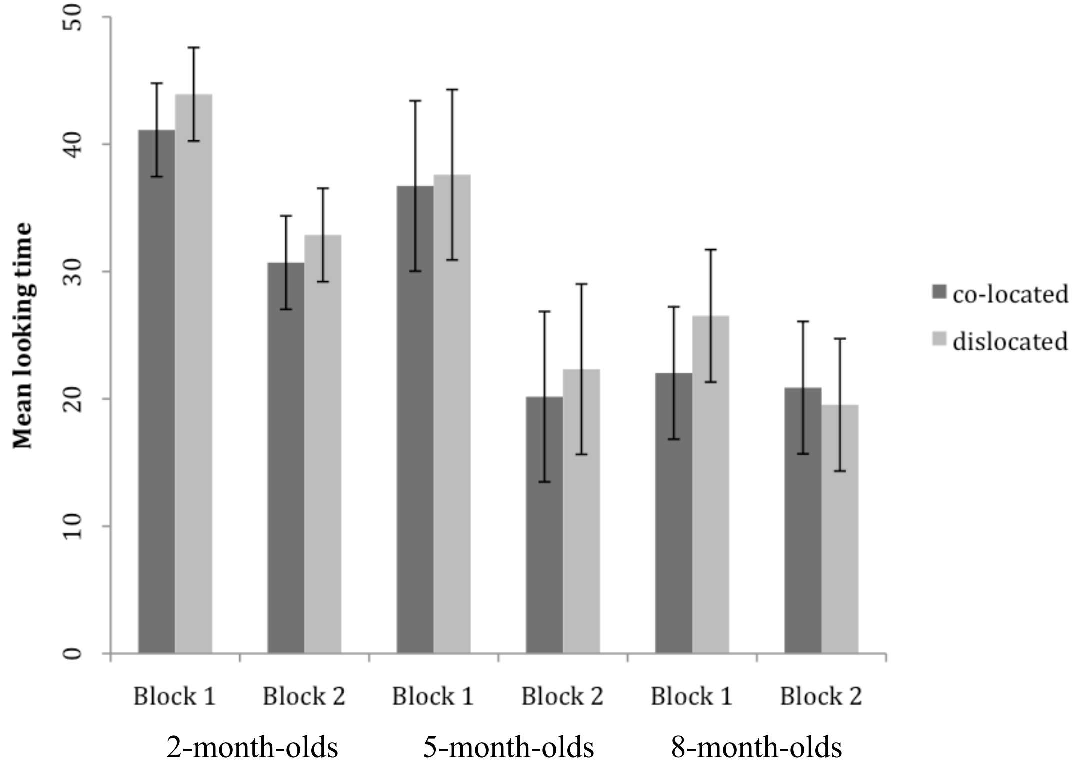
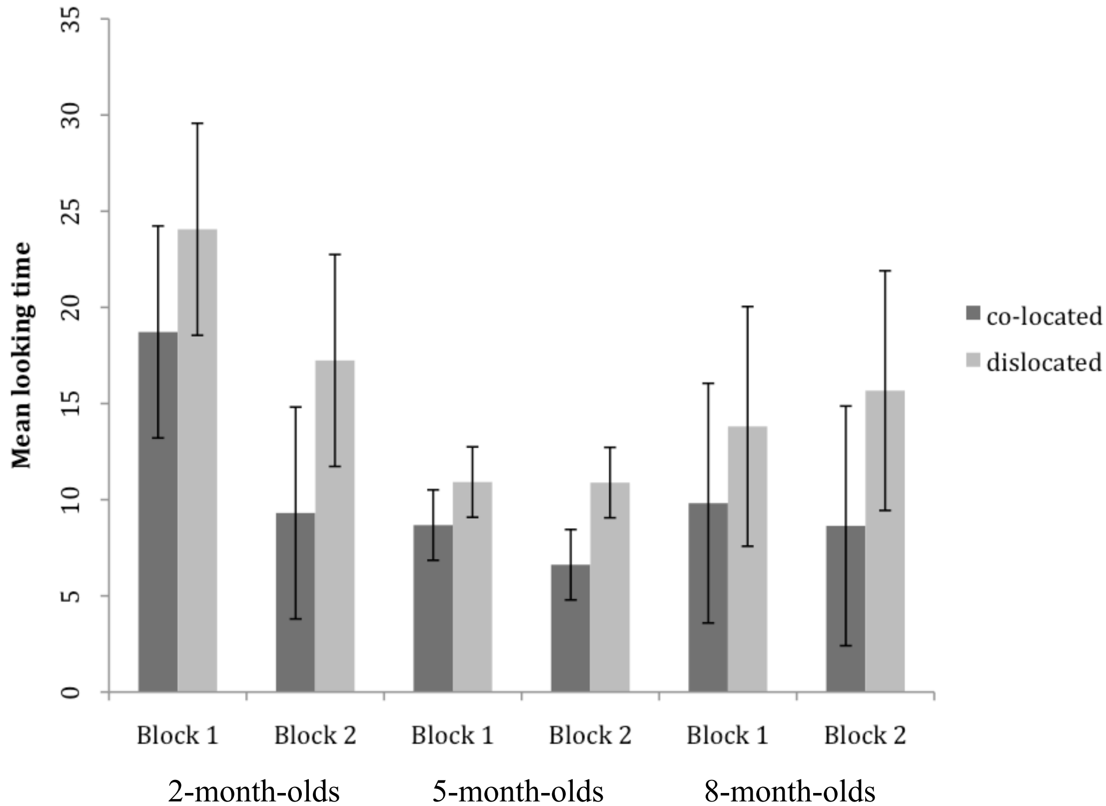


Figure 1



50
40
30
20
10
0
Mean looking time
co-located
dislocated
Block 1
Block 2
Block 1
Block 2
Block 1
Block 2
2-month-olds
5-month-olds
8-month-olds

Figure 2


Mean looking time
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5
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15
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25
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35
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Block 2
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Block 1
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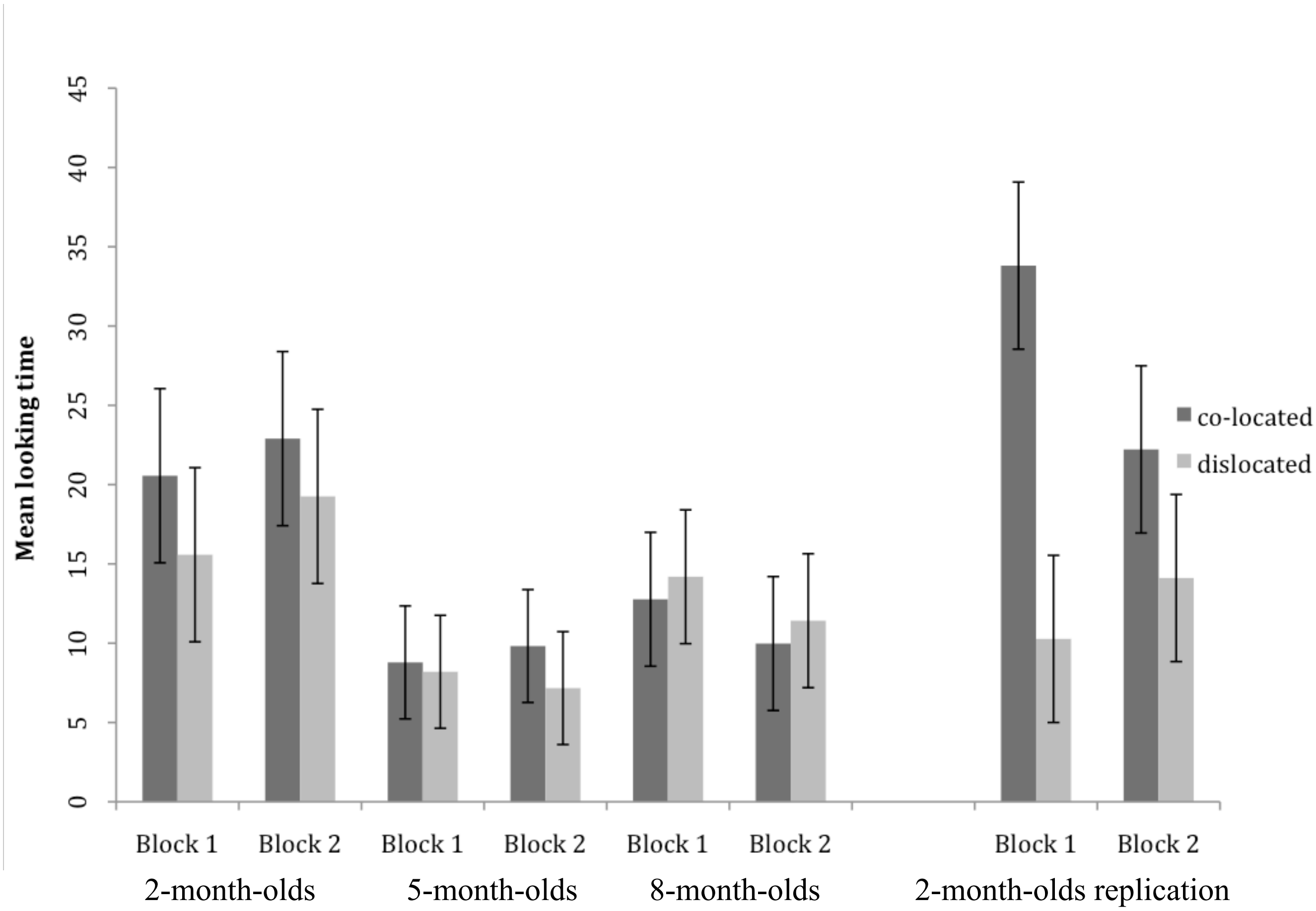
dislocated
2-month-olds
5-month-olds
8-month-olds

Figure 3


Mean looking time
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co-located
dislocated
Block 1
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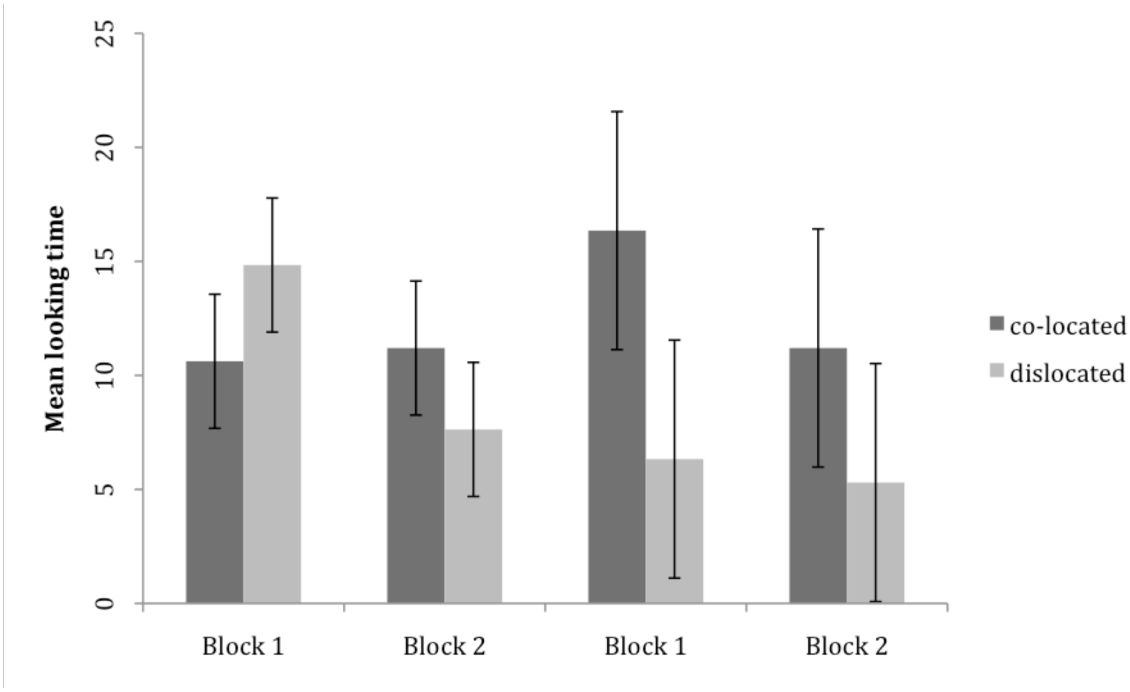
2-month-olds
5-month-olds
8-month-olds
2-month-olds replication

Figure 4



5-month-olds 8-month-olds

Figure 5