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The effects of auditory information on 4-month-old infants' perception of trajectory continuity.

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Abstract

Young infants perceive an object's trajectory as continuous across occlusion provided the temporal or spatial gap in perception is small. In three experiments involving 72 participants we investigated the effects of different forms of auditory information on 4-month-olds' perception of trajectory continuity. Provision of dynamic auditory information about the object's trajectory enhanced perception of trajectory continuity. However, a smaller positive effect was also obtained when the sound was continuous but provided no information about the object's location. Finally, providing discontinuous auditory information or auditory information that was dislocated relative to vision had negative effects on trajectory perception. These results are discussed relative to the intersensory redundancy hypothesis and emphasise the need to take an intersensory approach to infant perception.

The effects of auditory information on 4-month-old infants' perception of trajectory continuity.

Infants' response to moving object occlusion events in which an object passes behind an occluder has a long history as an indicator of infants' awareness of object persistence or permanence (Bower, Broughton, & Moore, 1971; Goldberg, 1976; Moore, Borton, & Darby, 1978). This early work relied on detecting anticipation of object re-emergence following occlusion. But alternative interpretations of anticipation were identified (Goldberg, 1976; Moore et al., 1978) that led to the conclusion that, on its own, anticipation of re-emergence did not safely indicate that the infant had interpolated the missing segment of the object's trajectory. Instead, it was possible that infants were anticipating a repeated cycle of discrete events each side of the occluder rather than the emergence of a single persisting object (Goldberg, 1976).

More recently, precise eye-tracker measures of visual tracking (Gredebäck, & von Hofsten, 2004; Johnson, Amso, & Slemmer, 2003a; Rosander & von Hofsten, 2004) and habituation novelty data (Bremner, Johnson, Slater, Mason, Foster, Cheshire, & Spring, 2005; Bremner, Johnson, Slater, Mason, Cheshire, & Spring, 2007; Johnson, Bremner, Slater, Mason, Foster, & Cheshire, 2003b) have produced converging evidence. This work has led to the conclusion that infants' ability to perceive an object's trajectory as continuous improves over the early months after birth (Figure1 illustrates the habituation novelty displays used). Specifically, 2-month-olds appear unable to perceive trajectory continuity (Johnson et al. 2003b), whereas 4-month-olds perceive trajectory continuity when the spatial or temporal gap in perception is small (Bremner et al., 2005; Johnson et al., 2003b), and 6-month-olds' ability appears to be well developed (Johnson et al., 2003a, 2003b). This has led some investigators to conclude that there are perceptual origins for object identity and permanence (Bremner et al., 2005; 2007, Johnson et al., 2003b): As infants become increasingly able to detect and retain information specifying perceptual completion, such as collinearity and temporal contiguity, their ability to recognize relations among disparate parts of a visual scene begins to improve. And these perceptual advances form the basis for development of awareness of object identity and permanence.

These studies presented information for the object's trajectory solely in the visual modality. However, there is evidence indicating modification of very young infants' response to visual stimuli following auditory stimulation, indicating intersensory matching and interaction of stimulus intensity (Lewkowicz & Turkewitz, 1980; 1981). Also there is strong evidence that redundant presentation of information across modalities recruits infant attention and enhances learning (the intersensory redundancy hypothesis [IRH]: Bahrick, Flom, & Lickliter, 2002; Bahrick & Lickliter, 2000; Bahrick, Lickliter, & Flom, 2004).

With respect to object movement, it has been demonstrated that 6-month-old infants are sensitive to congruence between timing of a sound and timing of a change in object movement direction, and that this sensitivity is dependent on spatial contiguity between auditory and visual stimuli (Lawson, 1980). And recently it has been demonstrated that infants from 2 to 8 months of age detect auditory-visual congruence and incongruence in events involving moving visual objects and stereophonically simulated moving sounds (Bremner, Slater, Johnson, Mason, Spring, & Bremner, in press). During habituation trials, infants detected congruence of visual and auditory information for movement and showed recovery of attention when the two sources of information became incongruent, specifically, when the auditory stimulus appeared to move left to right as the visual stimulus moved from right to left, and vice versa.

Evidence of infants' sensitivity to intersensory information about an object's trajectory raises the issue of whether providing auditory as well as visual information about an object's trajectory would enhance young infants' perception of trajectory continuity across an occlusion. According to the intersensory redundancy hypothesis, optimum conditions for deriving benefit from provision of multisensory information would be those in which both visual and auditory information provide congruent information about an object's trajectory. Under such conditions, visual and auditory information would specify the object's trajectory redundantly, and so could be expected to enhance perception of trajectory continuity as the object passed behind an occluder. However, in the present case there is an additional reason why supplementing the visual event with auditory information might enhance perception of trajectory continuity. Specifically, although there is a discontinuity in visual perception of the object as it passes behind an occluder, auditory information arising from a sounding object need not show this discontinuity. And although sound intensity generally reduces when an object passes behind an occluder, sound is not usually eliminated and may not reduce sufficiently to be detected by infants.

In order to benefit from presentation of intersensory information regarding an object's trajectory, it is of course necessary that infants are capable of localising sound with sufficient accuracy to detect change in location from sound alone. Some investigators have detected a more or less linear increase in localisation ability with age (Morrongiello, 1988; Morrongiello, Fenwick, & Chance, 1990), whereas other work suggests that auditory localisation is hard to elicit at around 2 months (Clifton, Morrongiello, Kulig, & Dowd, 1981; Field, Muir, Pilon, Sinclair, & Dodwell, 1980; Muir, Clifton, & Clarkson, 1989). However, although 4-month-olds' auditory localisation ability falls well short of adult levels, it is well established, with a minimum discriminable auditory angle of around 18 degrees (Morrongiello et al., 1990). And the fact that for static stimuli auditory-visual spatial co-location occurs in newborns (Morrongiello, Fenwick, & Chance, 1998) and older infants (Morrongiello, Fenwick, & Nutley, 1998), and that it occurs from two months upwards in the case of moving stimuli (Bremner et al. in press), indicates that auditory localisation is sufficient to detect information specifying object location and change in location.

In the series of experiments reported here we investigate different levels at which auditory information may benefit perception of trajectory continuity. In Experiment 1 we investigate the effect of supplementing visual information with continuous dynamic auditory information specifying the object's trajectory. In Experiment 2 we investigate whether effects of auditory information are limited to the case in which the sound provides dynamic information for movement, or whether such effects also occur when static auditory information specifies continuity over time but does not provide information for movement. In Experiment 3 we investigate two cases in which auditory information may be expected to detract from perception of continuity, one in which the sound disappears and reappears suddenly when the visual object disappears and reappears, and one in which the sound specifies motion in the opposite direction from that specified by vision.

Experiment 1

In this and the following experiments, we adopted the habituation novelty technique that had proved successful in previous work on trajectory continuity. Infants are habituated to an event in which an object moves back and forth, disappearing and reappearing behind a centrally placed occluder. Following habituation, they are presented with sequential test trials with the occluder absent and the object moving either continuously or discontinuously, in the latter case disappearing and reappearing as it did during habituation (see Figure 1). The rationale is that if infants perceived the habituation event as an object moving on a continuous trajectory, they should show a novelty preference for the discontinuous test display, whereas if they perceived a discontinuous trajectory during habituation they should show a novelty preference for the continuous test display. Johnson et al. (2003b) demonstrated that 4-month-olds' perception of trajectory continuity depended on the occluder width used, and Bremner et al. (2005) demonstrated that this age group perceived trajectory continuity provided either the time or distance out of sight was short. As the starting point for our investigation, we replicated conditions from earlier work, adding a continuous sound that stereophonically specified the object's trajectory. We selected two conditions from Johnson (2003b). One used a wide occluder that led the 4-month-olds to perceive trajectory discontinuity, and the other used a narrow occluder that had resulted in an intermediate null response, suggesting that 4-month-olds neither perceived continuity nor discontinuity in the trajectory presented during habituation. A second reason for our choice of these conditions was that we knew that these effects without sound were robust: the result with the wide occluder was replicated by Johnson et al. (2003b) and the null result with the narrow occluder was replicated in a subsequent study (Bremner et al., 2005). Thus, we were confident that we had reliable performance baselines without the need for further replication.

Method

Participants. Twenty-four 4-month-old infants (*M* = 120.5 days; range 112-136 days; 9 girls and 15 boys) took part in the experiment. A further 9 did not complete testing due to fussiness and 2 infants failed to habituate and so their data were not included. Twelve infants were assigned to each of the two experimental conditions in such a way as to ensure that the mean age and the gender balance were comparable across conditions. Throughout the series, infants took part in only one experiment. 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 and Stimuli. A Macintosh computer and a Samsung 100 cm color monitor were used to present stimuli and collect looking time data. An observer viewed the infant on a second monitor, and infants were recorded onto videotape for later independent coding of looking times by a second observer. Both observers were unaware of the hypothesis under investigation. Using HABIT software (Cohen, Atkinson, & Chaput, 2000) the computer presented displays, recorded looking time judgments, calculated the habituation criterion for each infant, and changed displays after criteria were met. The observer's judgments were input with a key press on the computer keyboard.

The habituation display consisted of a stationary centrally placed blue occluder with vertical extent 21.5 cm (12.3 degrees) and horizontal extent either 17.7 cm (10.1 degrees) or 14.8 cm (8.5 degrees) and a 6.7 cm (3.8˚) green ball undergoing continuous lateral translation back and forth at a rate of 16.8 cm/s (9.6˚/s), the center of its trajectory concealed by the occluder (see Figure 2). In the case of the wide occluder the ball was visible on either side of the occluder in its entirety for 1,067 ms, and was completely occluded for 667 ms. In the case of the narrow occluder, the ball was visible in its entirety for 1,200 ms and was completely occluded for 533 ms. In both conditions the transition from full visibility to full occlusion or the reverse took 400 ms. The animation was run as a continuous loop for the duration of the trial. During habituation trials, a repetitive musical sound was presented through two speakers located immediately to the left and right of the display monitor at the height of the object's trajectory, so that it appeared to a small sample of adults to move congruently with the object. This effect was achieved through varying the balance at constant rate from one extreme in which the sound came from only one speaker, through equal volume at each speaker (and hence equal intensity at both ears of the listener) to the other extreme when sound only came from 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 extremes and mid point. Furthermore, the smooth alteration in balance may be assumed to create a smooth change in apparent location between midpoint and extremes. In test displays, which occurred in silence, the box was removed and the ball translated back and forth in the same way as in the habituation display. In the continuous trajectory test display, the ball was always visible. In the discontinuous trajectory display, the ball went out of and back into view by progressive deletion and accretion at a vertical linear boundary, just as in the wide or narrow occluder habituation display (i.e., with a wide or a narrow gap in the trajectory), but without a visible (i.e., color- or luminance-defined) occluding edge (Figure 1b illustrates this for the wide occluder condition). Objects were presented against a black background with a 12 x 20 grid of white dots measuring 48.8 x 33.0 cm (27.4 x 18.7˚) serving as texture elements.

Design. Infants were assigned randomly to one of the two conditions. They were first habituated to either the wide occluder or the narrow occluder ball-and-box stimulus, with synchronised auditory information for the object's location provided continually throughout each trial. The two test displays were then presented in alternation, three times each, for a total of six presentations. Test trials were presented in silence. Half the infants in each condition viewed the continuous trajectory first, and half viewed the discontinuous trajectory first. Because the test displays were identical to those used in Johnson et al. (2003b), control conditions involving test displays alone were not conducted, since null results were obtained in these conditions previously.

Procedure. Each infant was seated 100 cm from the display and tested individually in a darkened room. During habituation trials the ball-and-box 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. After this criterion was achieved, the sequence of 6 test trials was commenced. Timing of each trial began when the infant fixated the screen after display onset. The observer pressed a key as long as the infant fixated the screen, and released when the infant looked away. A trial was terminated when the observer released the key for two seconds or 60 s had elapsed. Between trials, a beeping target was shown to attract attention back to the screen. The second observer coded looking times from videotape for purposes of assessing reliability of looking time judgments. Interobserver correlations were high across the five experiments in this report (*M* Pearson $r = .99$).

Results & Discussion

Figure 3 presents average looking times to the two test displays for the wide and narrow occluder conditions, respectively. Infants in both conditions looked longer at the discontinuous test display. Looking time data in many cells were positively skewed, violating assumptions of homogeneity of variance required by ANOVA, so scores were log-transformed prior to analysis in all the experiments in this report (data in the figures are based on raw scores). A 2 (display: wide vs. narrow occluder) x 2 (test trial order) x 2 (test trial type: continuous vs. discontinuous) x 3 (test trial block) mixed ANOVA yielded a significant effect of test trial type, $F\ (1,20) = 15.01, p = .001, \eta_p^2 = .43$. This effect was general across conditions, because the interaction between test trial type and display was not significant, $F\ (1,20) = .02, p = .89, \eta_p^2 = .001$. There were no other significant main effects or interactions.

The significant novelty preference across conditions for the discontinuous test display indicates that with the addition of auditory information for the object's trajectory, infants perceived trajectory continuity. This is in contrast to the results obtained by Johnson et al. (2003b) in the absence of auditory information, in which case infants in the wide occluder condition showed a significant preference for the continuous test display, indicative of perception of trajectory discontinuity, and infants in the narrow occluder condition showed no preference for either display. Thus, this is a clear demonstration that provision of auditory information supported perception of trajectory continuity.

Experiment 2

It is tempting to conclude that the effectiveness of auditory information in supporting perception of trajectory continuity was due to the fact that it provided dynamic auditory information for the changing location of the object as it moved along its path. In addition to providing redundant information for the object's changing location, auditory information provides dynamic location information even when the object is out of sight. However, it is possible that it was simply the continuity of the sound that provided information for continuity of the object's trajectory. If this were the case, provision of a stationary sound for the duration of each trial might also be effective in specifying trajectory continuity. Thus, in Experiment 2 we repeated the two conditions of Experiment 1, but replaced the stereophonically generated 'moving' sound with a sound that appeared to come from the center of the display.

Method

Participants. Twenty-four 4-month-old infants (*M* = 125.3 days; range 109-134 days; 12 girls and 12 boys) took part in the experiment. A further 7 did not complete testing due to fussiness. Twelve infants were assigned to each of the two conditions in such a way as to ensure that the mean age and the gender balance were comparable across conditions.

Apparatus, stimuli, design, and procedure. These were identical to Experiment 1 in all respects other than the fact that the sound during habituation trials was presented with equal intensity at both speakers, and thus appeared to come from the middle of the display.

Results & Discussion

Figure 4 presents average looking times to the two test displays for the wide and narrow occluder conditions, respectively. In the case of the narrow occluder infants looked longer at the discontinuous test display, and in the case of the wide occluder they looked approximately equally at the two test displays. A 2 (display: wide vs. narrow occluder) x 2 (test trial order) x 2 (test trial type: continuous vs. discontinuous) x 3 (test trial block) mixed ANOVA yielded no significant effect of test trial type, F (1,20) = 1.04, $p = .32$, $\eta_p^2 = .05$. But there was a significant interaction between test trial type and test trial block, F (2,19) = 4.26, $p = .03$, $\eta_p^2 = .31$. This interaction is illustrated in Figure 5. On the first test trial block, the effect of test trial type was not significant, F

(1,20) = 2.19, $p = .15$, $\eta_p^2 = .1$. However, on blocks two and three there was a significant preference for the discontinuous test trial, F (1,20) = 5.56, $p = .03$, $\eta_p^2 = .22$. There was also a significant main effect of test trial block, F (2,29) = 6.87, $p = .006$, $\eta_p^2 = .42$, due to a reduction in looking at the test trials across blocks. Neither the interaction between test trial type and display, F (1,20) = .46, $p = .5$, $\eta_p^2 = .02$, nor the interaction between test trial type, test trial block, and condition, F (2,19) = .59, $p = .56$, $\eta_p^2 = .06$ was significant, so the significant effects can be taken to be general across conditions.

These results indicate that provision of a continuous stationary sound during habituation trials also enhanced perception of trajectory continuity. However, this was only evident after the first test trial block, suggesting a more subtle effect that took some time to become evident. A possible reason for the delay in the effect relates to the novelty of both test trials relative to the habituation display: in both the occluder is absent and there is no sound. It is possible that one or both of these sources of novelty initially swamped a relatively subtle effect of a static sound during habituation. However, note that no such effect was evident in Experiment 1, which adds to the conclusion that the effect of a static sound is less marked than that of a dynamic sound.

Experiment 3

In our final experiment we posed the question of whether there were conditions under which provision of auditory information would impact negatively on perception of trajectory continuity. Given the conclusion from Experiment 2 that simply the continuity of a sound enhanced perception of trajectory continuity, we might suppose that providing a discontinuous sound might have the opposite effect. Thus, in one condition we again presented a dynamic sound during habituation, but it terminated abruptly at the moment when the object disappeared and then commenced again when the object began to reappear from behind the occluder. Another condition that seemed likely to disrupt trajectory perception involves provision of auditory information for the object’s location that conflicts with information provided by vision. Thus in a second condition we provided a dynamic auditory stimulus that was displaced relative to the visual object, and appeared to travel in the opposite direction to it.

We may consider both these conditions in relation to the intersensory redundancy hypothesis. In the first case, while the object is in view information about its path is specified redundantly across the two senses. However, there is a lower level of redundancy with respect to common onset and offset of both stimuli. As in Experiments 1 and 2, there is common onset and offset of visual and auditory stimuli at the beginning and end of each habituation trial. Additionally, in this condition there is common offset and onset when the object disappears and reappears from behind the occluder. At first sight, this suggests enhanced redundant presentation that should recruit attention. However, common offset and onset at the occluder boundaries presents redundant information for discontinuity. So this manipulation should increase the tendency to process the trajectory as discontinuous. In the second condition, there is common onset and offset of auditory and visual information at the beginning and end of each trial, however, there is no redundant information about the object's trajectory. In fact, across each trial the dynamic information is actually conflicting (dislocated) between modalities. Thus, again it can be predicted that such a condition should disrupt perception of trajectory continuity. In this experiment we chose to use only the narrow occluder display. Compared with the wide occluder display that led to perception of discontinuity when no auditory information was presented (Johnson et al., 2003b), this occluder width led to a null result and thus constituted the condition most likely to reveal a detrimental effect of auditory information relative to unimodal presentation.

Method

Participants. Twenty-four 4-month-old infants (*M* = 124 days; range 107-139 days; 14 girls and 10 boys) took part in the experiment. A further 2 did not complete testing due to fussiness, and one infant failed to habituate and so the data were not included. Twelve infants were assigned to each of the two conditions in such a way as to ensure that the mean age and the gender balance were comparable across conditions.

Apparatus, stimuli, design, and procedure. These were identical to previous experiments other than in the form of the auditory information presented during habituation trials, and in the fact that only the narrow occluder display was used. In the discontinuous sound condition, a dynamic sound of the sort used in Experiment 1 was presented, but it went off abruptly at the point when the object became fully hidden by the occluder and resumed abruptly when the object began to re-emerge. In the dislocated sound condition, the same sound was used as in Experiment 1, but it cycled back and forward such that when the object was at the right hand end of its cycle the sound was at the left hand end, and vice versa.

Results & Discussion

Figure 6 illustrates the results of Experiment 3. A 2 (condition: discontinuous vs. dislocated) x 2 (test trial order) x 2 (test trial type: continuous vs. discontinuous) x 3 (test trial block) mixed ANOVA revealed an overall trend towards perception of discontinuity, as shown by greater looking at the continuous display, F (1,20) = 2.85, $p = .11$, $\eta_p^2 = .13$, qualified by a test trial x test trial order interaction, F (1,20) = 11.58, $p = .003$, $\eta_p^2 = .37$. Exploration of this interaction indicated that there was significant perception of discontinuity when the first test trial was continuous, F (1,20) = 12.24, $p = .006$, $\eta_p^2 = .55$, but not for the opposite order, F (1,20) = 1.56, $p = .24$, $\eta_p^2 = .13$ (see Figure 7). There was neither a significant interaction between test trial type and condition, F (1,20) = .31, $p = .59$, $\eta_p^2 = .15$, nor a significant interaction between test trial type, condition, and test trial order, F (1,20) = .004, $p = .95$, $\eta_p^2 = .0$. Thus, we may conclude that the significant interaction between condition and test trial order is general across the two conditions. This effect cannot be explained by a general decline in looking across test trials because there was no significant effect of test trial block, F (2,19) = .27, $p = .76$, $\eta_p^2 = .03$.

These results confirm our prediction that presentation of both discontinuous and dislocated auditory information would have a detrimental effect on infants' perception of continuity of the visual event. However, the effect was limited to the case in which infants experienced the continuous test display first in the alternating sequence. Given that this cannot be interpreted as a simple order effect, the most plausible interpretation is that infants processed the habituation displays as discontinuous but only showed a novelty preference for the continuous test trial when it occurred first in the test trial sequence. When the discontinuous test trial was presented first, its novelty resulting from absence of occluder and sound may have attracted attention to these perceptual changes rather than continuity versus discontinuity. Of course, this effect did not occur in other experiments in this series. Although it is unclear just why it would have occurred in this experiment, we believe this constraint on the effect attests to the relatively weak negative effect of these forms of auditory information. This is in keeping with the conclusion that it is simpler to propel young infants along their developmental trajectory towards veridical perception than it is to do the opposite (Bremner et al., 2005). Specifically, once the ability to perceive trajectory continuity has begun to emerge, it may take relatively little to support its further emergence. In contrast, development of perceptual constraints may attune infants selectively to veridical information and reduce the effectiveness of non-veridical information such as incongruent or abruptly discontinuous auditory information.

General discussion

This series of experiments demonstrates clearly that the addition of auditory information can affect young infants' perception of trajectory continuity. The strongest positive effect was obtained in Experiment 1 in which dynamic auditory information about the object's trajectory led to perception of trajectory continuity. And this occurred under occlusion conditions in which, in the absence of auditory information, 4-month-old infants either perceive the trajectory as discontinuous or form no clear percept of it as continuous or discontinuous. The strength of this effect is in keeping with the predictions of the intersensory redundancy hypothesis (IRH), because in Experiment 1 information about the object's changing location was presented redundantly across auditory and visual modalities. However, a rather weaker effect also emerged in Experiment 2 when the sound was continuous but provided no information for the object's changing location. This finding is again consistent with the IRH, because redundancy existed in terms of common stimulus onset, offset, and duration. Infants were generally looking away when trials ended, meaning that common offset and common duration were unlikely to be detected. However, common onset may constitute sufficient redundancy to recruit attention to the visual event and enhance trajectory perception. An alternative possibility, also in keeping with the IHR, is that continuity of the sound across the period during which the object was out of sight supported perception of trajectory continuity. The result in the discontinuous sound condition of Experiment 3 supports this interpretation. A discontinuous dynamic sound, like a dislocated dynamic sound, had a negative effect on perception of trajectory continuity. Although in both these conditions there was common onset of auditory and visual events, in Experiment 3 this information is probably insufficient to support perception of trajectory continuity because conflicting information was also present. In the discontinuous sound condition auditory information specified discontinuity of trajectory, and the dislocated sound condition markedly eliminated the spatio-temporal relationship between visual and auditory information.

Rather than pointing to a shortcoming of the IRH, these results suggest an extension of the hypothesis for the particular case of perception of trajectory continuity. It seems likely that there is a hierarchy of auditory information that is more or less likely to influence perception of trajectory continuity. The most precise information for trajectory continuity is information about the continuous change in the object's location. Presenting this spatiotemporal information redundantly across the parts of the cycle in which the object is visible may act to fill in the gap in visual perception when the object passes behind the occluder (Experiment 1). However, dislocated or discontinuous presentation of this information (Experiment 3) provides conflicting or discontinuous spatiotemporal information and disrupts perception of continuity. At a lower level, providing a continuous stationary sound provides temporal information for continuity that enhances perception of trajectory continuity (Experiment 2). Finally, in all the current experiments, common onset information may have recruited attention to the habituation display. But if so, its effects were outweighed by the negative effects of discontinuity or dislocation of auditory information.

An important finding emerging from work on intersensory perception concerns the developmental sequence in which different intersensory properties are detected. Temporal synchrony is detected early and is followed by detection of information about stimulus duration, temporal rate and rhythm. And it is argued that temporal synchrony forms the basis for development of the later detected properties (Lewkowicz, 2000). In the present work, common onset is a case of temporal synchrony, and there is an interesting question of whether benefit from amodal auditory-visual information for trajectory would be lost if there was not common onset between auditory and visual information. However, the importance of synchrony between dynamic auditory and visual information for movement lead us to conclude that this cue may be primary in dynamic events of the sort we have investigated. This dynamic auditory-visual spatial co-location is a case of dynamic spatio-temporal synchrony, in which the auditory left-right cycle is in phase relative to the visual cycle. Future work should investigate the developmental relationship between this form of synchrony and detection of other properties of object trajectories such as rate and extent of movement. If there is a parallel with other work on intersensory perception, dynamic spatial co-location should form the basis for later development of sensitivity to other intersensory properties of object trajectories.

At a general level, these results both extend our understanding of young infants' perceptual abilities and attest to the importance of taking a multimodal approach. Existing work suggests that 4-month-olds have a rather fragile ability to perceive object trajectories, but that this ability is readily facilitated and enhanced by reducing the processing demands of the task (Bremner et al., 2005; Jonson et al., 2003 a or b?). The present results are a clear demonstration that supplementing visual information with auditory information can enhance 4-month-old infants' perception of object trajectories. As such, this is further demonstration of the essentially multimodal nature of infant perception. Furthermore, many objects in the infant's everyday environment emit sounds as they move. We may speculate that infants first begin to interpolate the path of an object that is temporarily lost to sight under circumstances in which auditory information continues to provide information about its trajectory, and in general, when there is amodal auditory-visual information for the object's trajectory when the object is in view. In parallel with findings regarding infants' perception other spatiotemporal properties such as rhythm and tempo (Bahrick & Lickliter, 2004) we may predict that older infants will be less dependent on multimodal information for object trajectories, showing more robust unimodal perception of object trajectories. However, when auditory-visual information for movement is present, we may expect infants to develop increasing sensitivity to incongruence between the senses. Bremner et al. (in press) demonstrated that 2-month-olds were capable of learning an incongruent dynamic auditory-visual relationship whereas older infants only did so with additional training. We may speculate that this developmental effect is the result of accumulated experience of congruent auditory-visual information in everyday events. This, along with improvements in infants' capacity for auditory localisation, may make them sensitive to increasingly subtle incongruence between auditory and visual information for object movement.

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Figure captions

Figure 1: Schematic depiction of events shown to infants in Johnson et al. 2003b) to gauge perception of trajectory continuity. A: Habituation event. A ball moves behind an occluding screen and re-emerges, then returns on a repetitive cyclic trajectory. B: Discontinuous trajectory test event. The ball moves to the place occupied previously by the occluder and goes out of sight in the same manner. C: Continuous trajectory test event. The ball moves back and forth as before but remains visible during the entire trajectory. The rationale is that if infants perceived trajectory continuity during habituation they should show a novelty preference for the discontinuous test trial.

Figure 2: The wide and narrow occluder habituation displays used in Experiments 1 and 2. Test displays were as illustrated in Figure 1, with the 'gap' in the discontinuous display matched to the width of the habituation occluder.

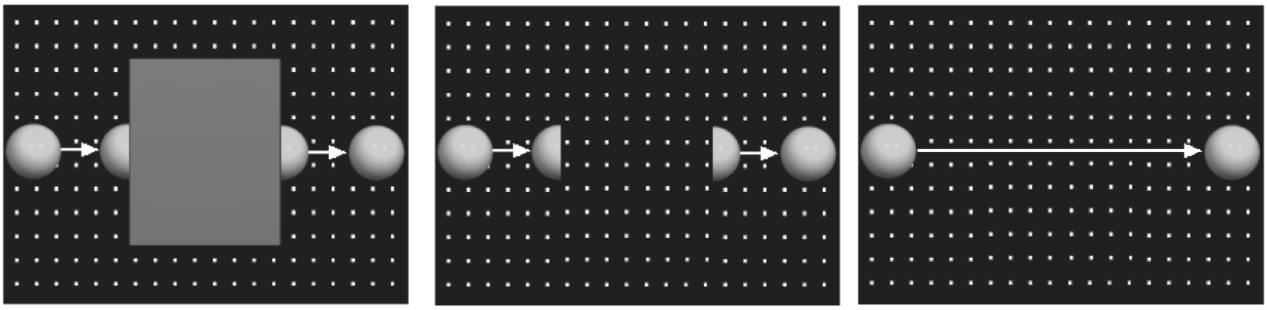
Figure 3: Mean looking times to the two test displays for wide and narrow occluder conditions in Experiment 1. Error bars in this and subsequent data figures display standard errors.

Figure 4: Mean looking times to the two test displays for wide and narrow occluder conditions in Experiment 2.

Figure 5: Mean looking times to the two test displays by test trial block in Experiment 2.

Figure 6: Mean looking times to the two test displays in the discontinuous and dislocated conditions of Experiment 3.

Figure 7: Mean looking times to the two test displays for the two test trial orders in Experiment 3.



A

B

C

Figure 1

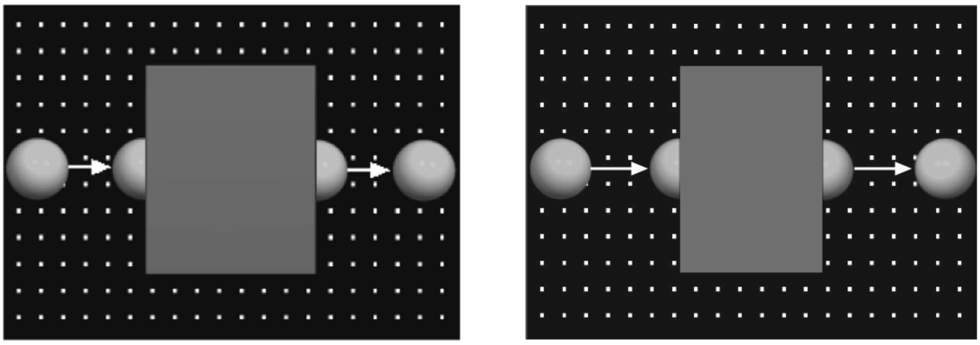


Figure 2

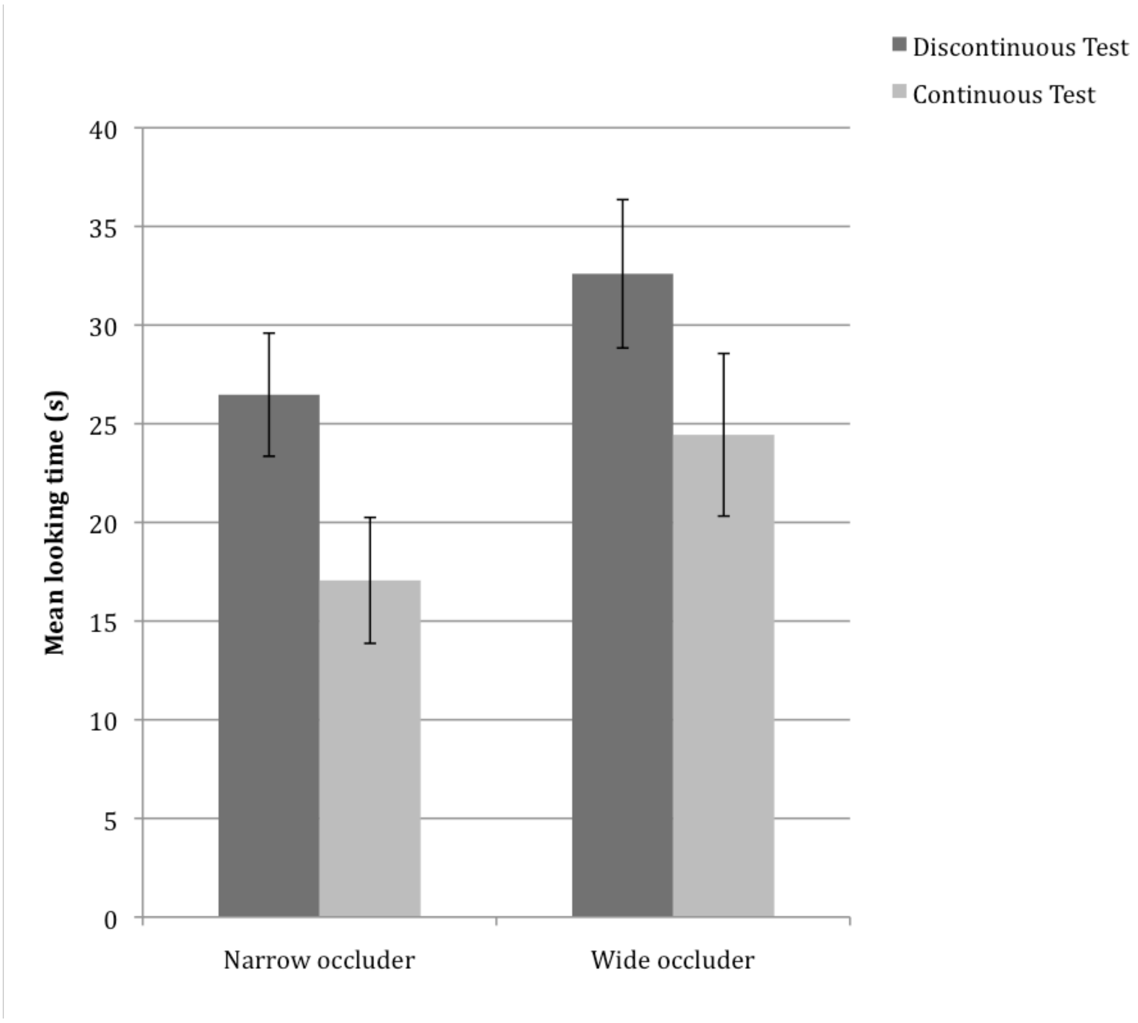

Discontinuous Test
Continuous Test
Mean looking time (s)
40
35
30
25
20
15
10
5
0
Narrow occluder
Wide occluder

Figure 3

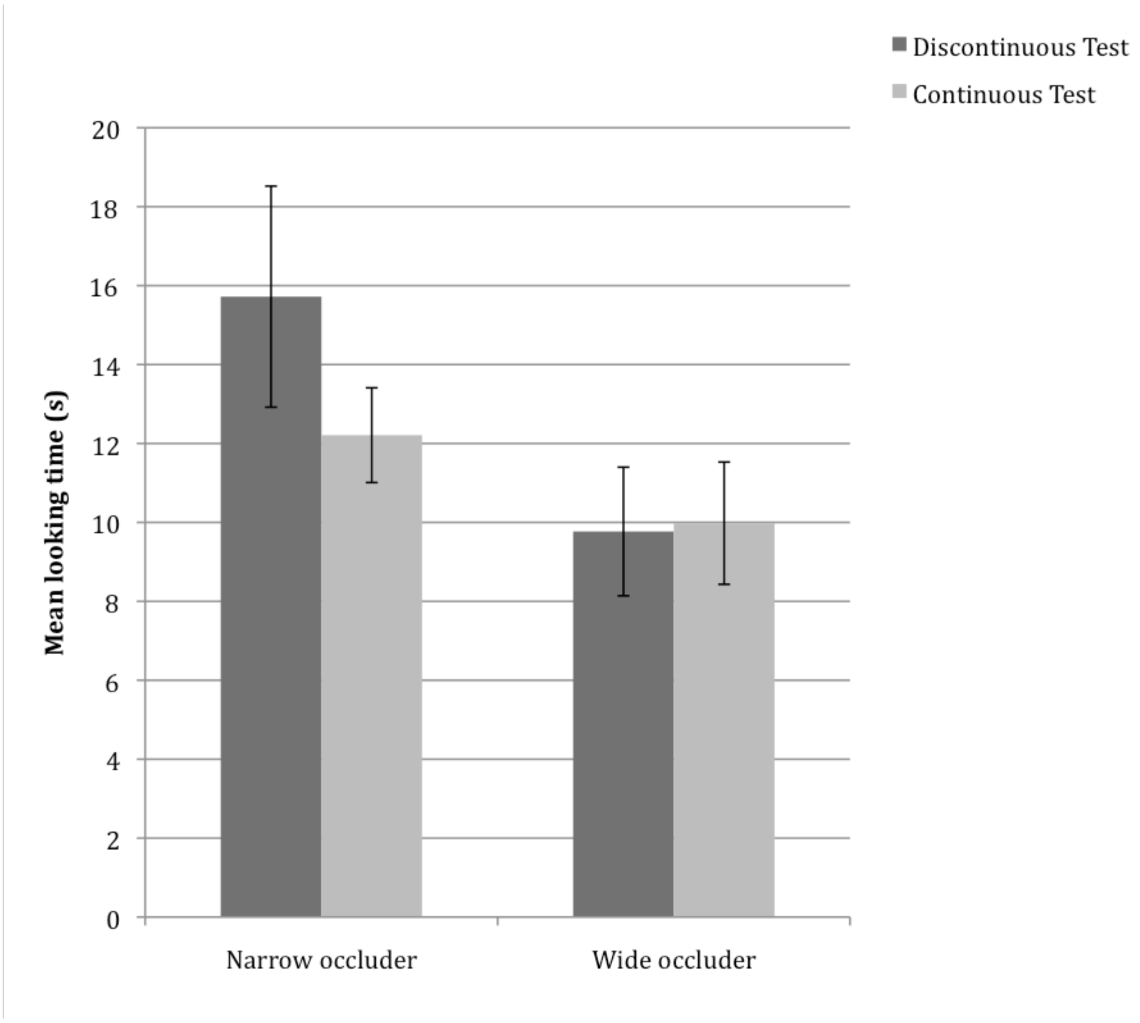

Discontinuous Test
Continuous Test
Mean looking time (s)
0
2
4
6
8
10
12
14
16
18
20
Narrow occluder
Wide occluder

Figure 4

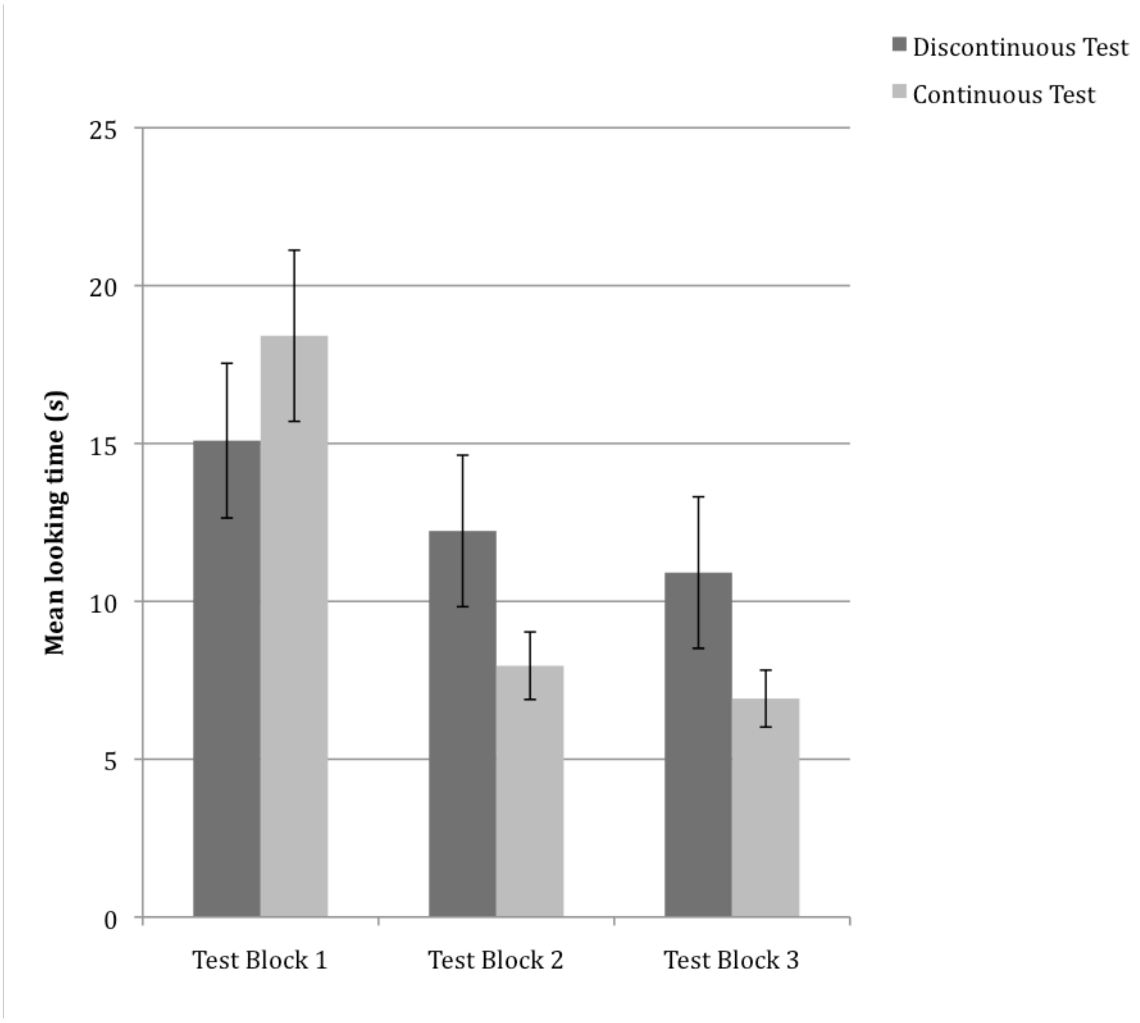

Discontinuous Test
Continuous Test
Mean looking time (s)
25
20
15
10
5
0
Test Block 1
Test Block 2
Test Block 3

Figure 5

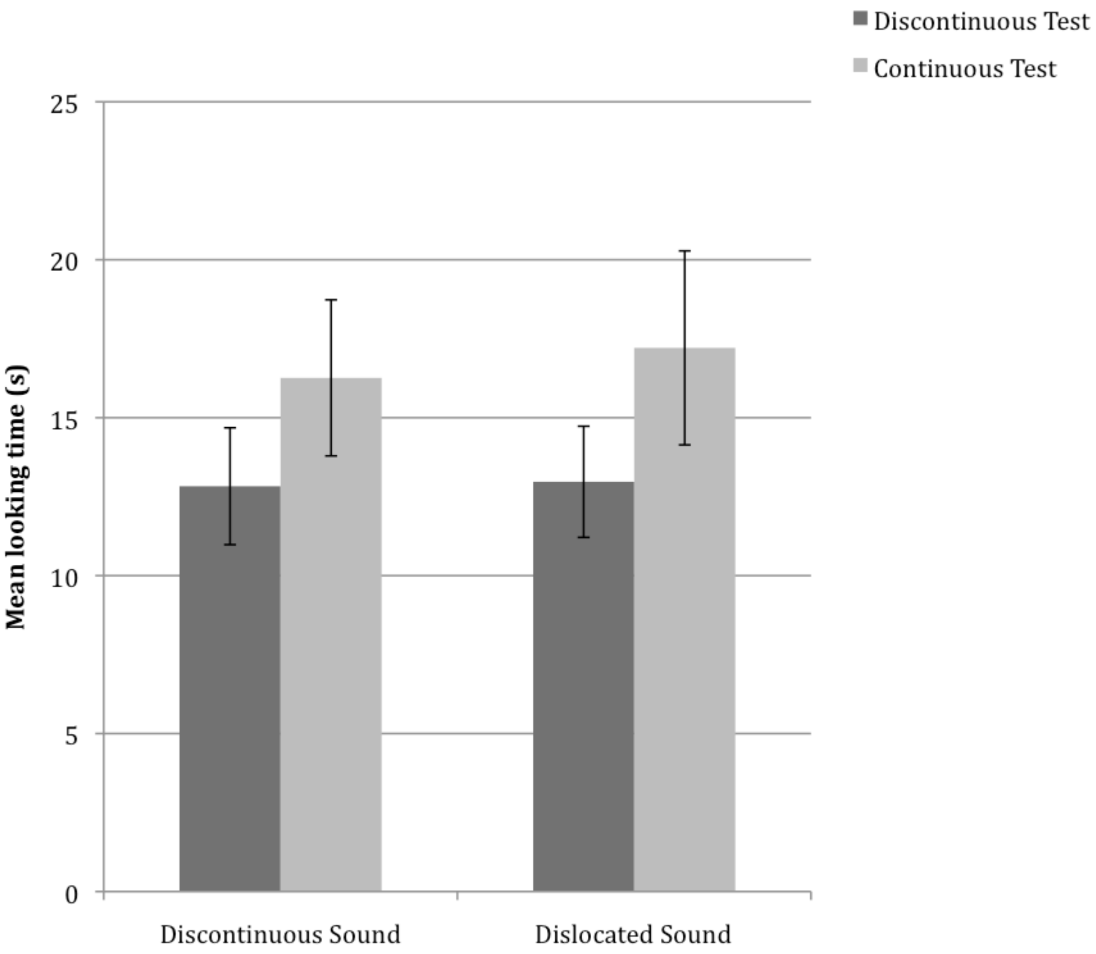

■ Discontinuous Test
■ Continuous Test
Mean looking time (s)
25
20
15
10
5
0
Discontinuous Sound
Dislocated Sound

Figure 6

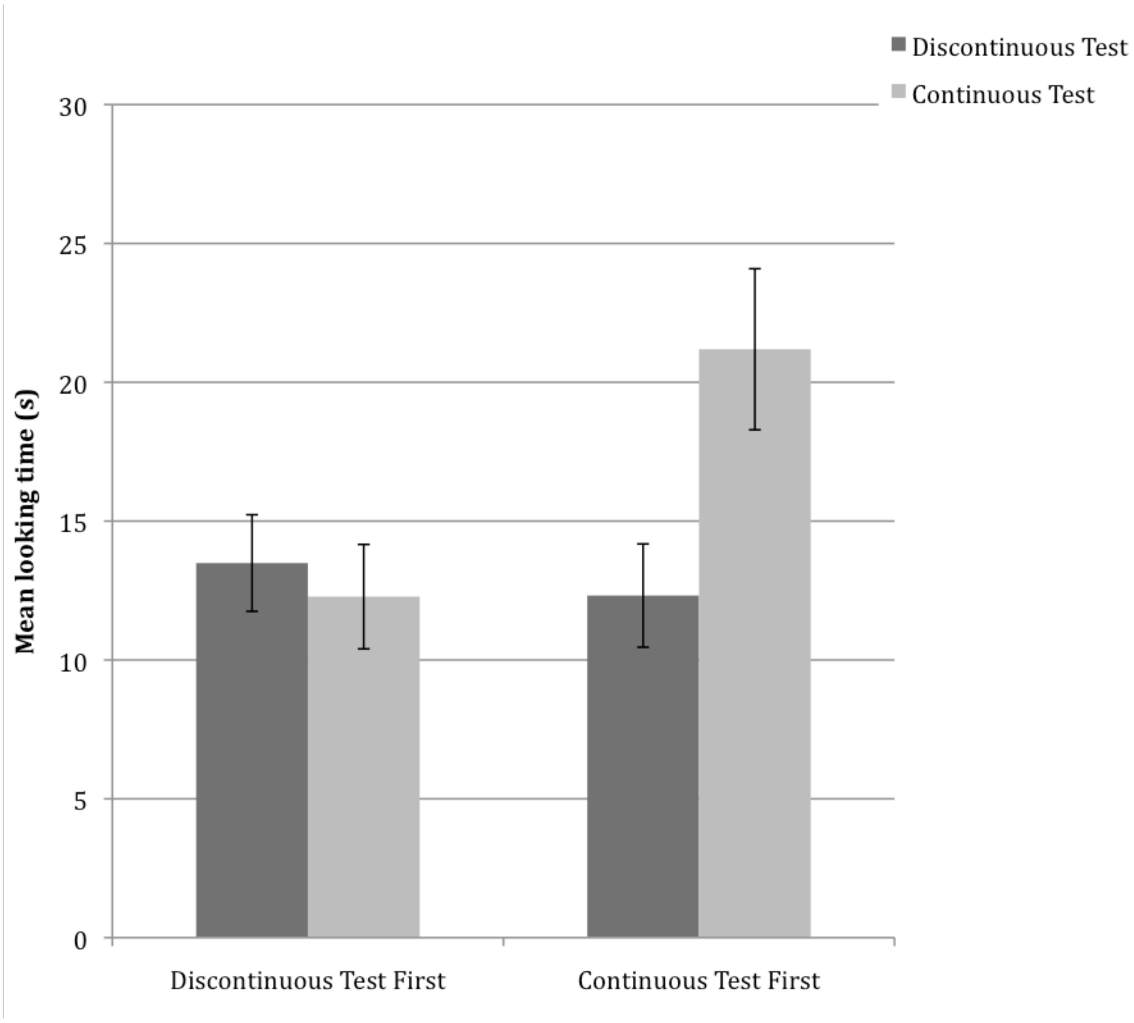

Discontinuous Test
Continuous Test
Mean looking time (s)
30
25
20
15
10
5
0
Discontinuous Test First
Continuous Test First

Figure 7