Susceptibility to the flash-beep illusion is increased in children compared to adults.

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Abstract

Audio-visual integration was studied in children aged 8-17 (N=30) and adults (N=22) using the "flash-beep illusion" paradigm, where the presentation of two beeps causes a single flash to be perceived as two flashes (*fission* illusion), and a single beep causes two flashes to be perceived as one flash (*fusion* illusion). Children reported significantly more fission illusions than adults, indicating that auditory and visual information was integrated more often, and less selectivity than in adults. Within either group, illusion reports did not correlate with either age or motor coordination measures. The current results show that the form of multisensory integration indexed by the illusion is slow to mature in normally-developing children.

Keywords: development, multisensory integration, auditory, visual

Susceptibility to the flash-beep illusion is increased in children compared to adults.

In the mature human brain, the process of multisensory integration (MSI) can result in significant perceptual advantages, particularly for stimuli where the temporal and spatial properties in each modality are congruent. For example, the detection of weak visual stimuli can be enhanced by concurrently presented sounds (Frassinetti, Bolognini, & Ladavas, 2002; Lovelace, Stein, & Wallace, 2003) and the intelligibility of speech is improved when video of the appropriate lip movements is available (MacLeod & Summerfield, 1987; Sumby & Pollack, 1954). This integration process generally improves perceptual estimates. However, if incongruent stimuli are presented to multiple sensory modalities, integration can still occur, resulting in altered or illusory percepts. In the ventriloquist illusion, for example, the perceived location of sound sources can be strongly influenced by spatial visual information (Pick, Warren, & Hay, 1969; Welch & Warren, 1980), and video of incongruent mouth movements can affect the perception of speech (McDonald, Teder-Salejarvi, Di Russo, & Hillyard, 2003; McGurk & MacDonald, 1976).

The ability to match or compare information from multiple sensory signals appears quite early in human development. For example, infants can match the intensities of auditory and visual signals (Lewkowicz & Turkewitz, 1980), discriminate between redundantly-specified auditory-visual tempos (Bahrick, Flom, & Lickliter, 2002), and at only 1-3 days post-natal are able to match non-native primate vocalisations to the appropriate visual gesture (Lewkowicz, Leo, & Simion, 2010). However, as with many unisensory abilities (such as speech perception (Kuhl, Tsao, & Liu, 2003), face perception (Pascalis, de Haan, & Nelson, 2002), and music perception (Hannon & Trehub, 2005)), some multisensory abilities present at birth or soon after show evidence of narrowing or tuning with post-natal development. For example, the ability to respond to an audio-visual primate phonetic contrast has been shown to narrow between 6 and 11 months of age (Pons, Lewkowicz, Soto-Faraco, & Sebastián-Gallés, 2009). This finding and many others (for review see Lewkowicz & Ghazanfar, 2009) suggests that post-natal experience with the appropriate stimulus-response contingencies is required in order to tune the matching processes to best suit the child's environment.

Multisensory abilities such as intensity matching (Lewkowicz & Turkewitz, 1980), audio-visual rhythm discrimination (Bahrick & Lickliter, 2000, 2004) and the detection of temporal equivalence in the form of speech onsets and offsets (Lewkowicz, 2010; Lewkowicz et al., 2010), can appear very early in infancy. Although these abilities appear to be present at birth (and are often subsequently refined or narrowed with post-natal experience), other multisensory phenomena emerge later in life. For instance, in the stream-bounce illusion (Sekuler, Sekuler, & Lau, 1997), the presentation of a brief click as two moving balls intersect on a video display biases the perception towards bouncing rather than streaming in adults. There is evidence from looking-time measures that infants of 6 and 8 months of age, but not 4 months of age, spend more time looking at the "streaming" display, where the sound is absent, than at the "bouncing" percept to which they are habituated (Scheier, Lewkowicz, & Shimojo, 2003a). The looking-time measures suggest that the streaming display, where the only difference is the lack of the click sound at the collision point, is visually novel. Although there is some controversy over the interpretation of looking time measures (see Scheier, Lewkowicz, & Shimojo, 2003b; Slater, 2003 for discussion), the evidence suggests that the illusion may not be perceived until at least 6 months of age. Similarly, Neil, Chee-Ruiter, Scheier, Lewkowicz and Shimojo (2006), found that spatial orienting responses to auditory-visual targets were facilitated in 8-10 month-old infants as well as adults, but not reliably in infants under 8 months of age.

Although the McGurk illusion has been found to occur in infants (Rosenblum, Schmuckler, & Johnson, 1997), incongruent visual stimuli have less of an effect on final phoneme perception in both 3-5 and 7-8 year-old children than in adults (Massaro, 1984; Massaro, Thompson, Barron, & Laren, 1986; McGurk & MacDonald, 1976). In both the McGurk and stream-bounce illusion cases, information from one sense alters or enhances perception in the other, requiring a more integrative process than tasks requiring the transfer or matching of information across the senses. Gori, Del Viva, Sandini, and Burr (2008) have likewise shown that judgements of size and orientation do not benefit from the ability to optimally integrate visual and haptic information until between 8 and 10 years of age, and Nardini, Jones, Bedford, and Braddick (2008) have shown that children up to 8 years of age do not integrate self-generated motion cues with visual cues in an object navigation task. Barutchu, Danaher, Crewther, Innes-Brown, Shivdasani and Paolini (2010), using a simple auditory-visual detection task, also found that reaction times to auditory-visual stimuli do not show mature super-additive enhancement in children as old as 11 years of age. Using a similar detection task, Brandwein, Foxe, Russo, Altschuler, Gomes and Molholm (2010) have recently shown that mature levels of multisensory facilitation (and associated auditory event-related potentials) are only reached by approximately 15 years of age. In summary, although infants can match information across the senses at a very young age, the facilitation of perceptual judgements and reaction times by the integration of multisensory stimuli is generally found to develop slowly throughout childhood.

Another multisensory illusion is the flash-beep illusion. In this illusion, the presence of a number of brief auditory stimuli affects judgments of the number of visual flashes presented (Shams, Kamitani, & Shimojo, 2000). When a single flash is paired with two or more beeps, participants often report seeing more than the single flash that was presented. This form of the illusion has been termed a *fission* illusion, as the double auditory stimulus is thought to split the perception of a single flash into two. The fission illusion has since been shown to be robust to a degree of temporal delay between the auditory and visual stimuli (Shams, Kamitani, & Shimojo, 2002), spatial separation of the auditory and visual stimuli across the visual midline (Innes-Brown & Crewther, 2009), and even accuracy feedback on each trial specifically designed to reduce its strength (Rosenthal, Shimojo, & Shams, 2009).

Several neuro-imaging studies (Bhattacharya, Shams, & Shimojo, 2002; Mishra, Martinez, Sejnowski, & Hillyard, 2007; Shams, Kamitani, Thompson, & Shimojo, 2001; Watkins, Shams, Tanaka, Haynes, & Rees, 2006) have shown that reports of the fission illusion are correlated with increased activity in primary visual cortex. These studies generally support the hypothesis that the illusion results from the integration of auditory and visual information, rather than the possible introduction of response biases. In a related sound-induced *fusion* illusion, a single beep causes the fusion of a double flash into the perception of a single flash. Neural correlates of the fusion illusion, measured using functional magnetic resonance imaging (fMRI - Watkins, Shams, Josephs, & Rees, 2007) and event-related potentials (ERP - Mishra et al., 2007), are correspondingly reduced in the same areas. In combination with the behavioural evidence, these findings of increased activity in V1 during perception of illusory extra flashes (fission) and reduced activity in V1 during illusory reduction of flashes (fusion) strongly suggest that the illusion occurs as a result of modification of activity in primary visual cortex by the auditory stimulus. Thus, reports of illusory fission or fusion of a visual stimulus by sound are indicators of integration at low levels in the brain, possibly in the primary visual cortex.

The flash-beep paradigm is simple to administer and suitable for assessing MSI in both adults and children. However, to our knowledge, only one study has investigated the flash-beep illusion in children (Tremblay et al., 2007). In this study, both the *fission* and *fusion* illusions were studied in children between 5-19 years of age, separated into three age groups. Both fission and fusion illusions were shown to occur in each age group; however, no significant differences in the number of illusions for either fission or fusion stimuli were found between any of the three age groups. As there was no gradual improvement or decline in accuracy with age, the authors interpret their results as consistent with theories suggesting that audio-visual integration abilities mature very early in life. However, illusions were reported more often (about 80% illusion responses in fission illusion trials) than previous studies have found in adults – generally around 50% illusion responses in fission illusion trials – (Andersen, Tiippana, & Sams, 2004; Courtney, Motes, & Hubbard, 2007; Innes-Brown & Crewther, 2009; Meylan & Murray, 2007; Shams et al., 2000, 2002). Given this difference, it is possible that the form of multisensory integration measured by the flash-beep illusion task is actually immature, and over-active in children, with auditory information being more often, but less selectively integrated with the visual signal. Without an adult control group completing the same paradigm, this possibility is difficult to assess.

In the present study, the objectives were to determine whether children showed less selective integration of auditory and visual temporal information than adults. Using the flash-beep paradigm to provide evidence of multisensory integration, reports of fission and fusion illusions by normally developing children were compared with adults. Six combinations of single and double flash/beep pairs were presented, including “fission” and “fusion” illusion stimuli where the numbers of flashes and beeps did not match. As the performance of children in the flash-beep task is still relatively unknown, multisensory control trials using congruent flash/beep stimuli were also presented, and unisensory visual-alone trials were presented to test whether the visual stimulus itself was unambiguous for both adults and children. Accuracy and reaction time measures were compared for adults and children with each stimulus type to determine the extent to which MSI caused incorrect reports of the flash stimuli. To determine any developmental trajectory, these measures were correlated with age within each group.

Methods

Participants

Fifty-two individuals participated in the study. Thirty participants under the age of 18 were assigned to the child group, and twenty-two over the age of 18 were assigned to the adult group[1]. The child group consisted of 14 girls and 16 boys, with a mean age of 11.1 years (SD=2.0, range 8-17 years). Children were recruited from schools in the Melbourne metropolitan area under the auspices of the Catholic Education Office, Melbourne, and came from a wide variety of socio-economic circumstances and cultural backgrounds. The adult group consisted of 12 females and 10 males with a mean age of 29.0 years (SD=5.8, range 19-42 years). All adult participants gave written informed consent, as did the parents of child participants. The study was approved by the Human Research Ethics Committee of the Royal Victorian Eye and Ear Hospital and by the Catholic Education Office, Melbourne. All participants were right-handed, had normal hearing, normal or corrected-to-normal vision, and reported no diagnosis of a psychological or neurological disorder.

[1] The oldest child was 17.0 years old, and the youngest adult was 19.0 years old. As these two participants ages fell close to the boundary dividing the adult and child groups, all analyses were repeated with these two individuals removed. No differences were found in the pattern of statistical significance across any of the analyses performed, so these individuals were included in the results.

Stimuli and apparatus

The experiment was conducted in a quiet sound-treated room with a background sound level of approximately 39 dB SPL (A-weighted). The visual stimulus consisted of a white disk, which flashed once or twice on a 20-inch cathode ray tube monitor (CRT) with a black background. The disk subtended 3° of visual angle and was located 7.5° below a fixation cross, which was positioned 2.5° above the centre of the screen. The refresh rate of the CRT was set to 160 Hz, and each flash consisted of two refresh periods (12.5 ms, see Figure 1). On selected trials, short beeps were presented, along with the flashes, from a speaker placed centrally under the CRT. The beep was a 3500 Hz, 83 dB SPL (A-weighted) sine wave of 8 ms duration, with 3 ms rise and fall times. The fixation cross remained present throughout each block. Participants sat in a comfortable armchair with the head 100 cm from the CRT. A response box rested on a desk at a comfortable distance directly in front of the CRT. The auditory and visual stimuli were generated by programmable real-time hardware (RX6 processor, Tucker-Davis Technologies, Alachua, FL; Visage, Cambridge Research Systems, Kent, England), which ensured that each beep onset could be exactly synchronised with the required refresh of the computer monitor.

All participants completed the Purdue Pegboard (Tiffin & Asher, 1948), a measure of manual dexterity where participants were asked to insert the maximum number of small pins into a row of sockets in a given time. The task was run using each hand alone (Pegboard-Left, Pegboard-Right) and with both hands (Pegboard-Both).

Procedure

The procedure broadly followed that outlined in the original report of the sound-induced flash phenomenon (Shams et al., 2002), except that a slightly reduced number of stimulus combinations was presented due to the time constraints imposed by testing young children, and a simplified stimulus timing scheme was used. Whereas Shams et al. (2002) presented the first beep 23 ms prior to the first flash, the onsets of each auditory and visual stimulus were exactly synchronised in the current procedure. This stimulus timing is simpler to interpret than that used in the original report, and has been used successfully in fMRI (Watkins et al., 2006) and ERP (Meylan & Murray, 2007) investigations of the flash-beep illusion.

On each trial, there were either one or two flashes, along with zero, one, or two beeps. Trials are henceforth referred to using a code indicating the number of flashes followed by the number of beeps – "2F2B" thus refers to a trial with two flashes and two beeps. In trials with multiple flashes or beeps, the time between the onsets of successive beeps or flashes was 75 ms, corresponding to 12 CRT refresh periods. An example of a 2F2B trial is shown in Figure 1.

*** INSERT FIGURE 1 HERE ***

Each trial began with the visual stimulus presented in the centre of the screen, below the fixation cross. Following each trial was a 2-3 s interval, during which the participant was required to indicate how many flashes were perceived by pressing one of two buttons on the response box. Participants were instructed to keep their gaze on the fixation cross during the whole trial block and to count the number of flashes that would appear while ignoring the beeps. They were instructed to press a button labelled either "1" or "2" depending on how many flashes they saw, and to make their best guess if unsure.

The six possible flash/beep combinations (1F0B, 1F1B, 1F2B, 2F0B, 2F1B, 2F2B) were randomly presented ten times each in a single block. This block was repeated six times (with trials re-randomised each time). Each stimulus was thus presented 60 times. Button-press responses and reaction times (RT) were recorded for each stimulus presentation. Responses were not analysed if they were made less than 100 ms or more than 1500ms post-stimulus. Each block ran for an average duration of two minutes and breaks could be taken between each block. The total testing time was approximately 20 minutes.

Analyses and Results

Purdue Pegboard

All tests of statistical significance are reported as significant if $p < .05$. As reaction times form an important part of the later analyses, it was important to obtain a baseline measure of the manual dexterity of all participants. Table 1 shows the mean scores (number of pegs inserted in 30 seconds) for all the pegboard sub-scales in each group. Since all participants were right-handed, and responded with their right hands, only the Pegboard-Right scores were included in later correlation analyses. Adults were significantly faster than children when using the left, right, or both hands (see Table 1). There were no significant differences between males and females in either group for any of the Pegboard measures.

*** TABLE 1 HERE ***

Flash-beep task – accuracy

Accuracy scores were analysed in order to determine whether participants could accurately count the visual flash stimuli either in the absence of an auditory stimulus or with a congruent number of beeps, and then to determine the extent of fission and fusion illusions reported in trials where an illusion was expected.

For each of the six stimulus types, accuracy scores were calculated by dividing the number of correct responses by the total number of valid responses made, so that non-responses were not counted as incorrect. Non-responses were rare, with 95.6% valid responses for adults and 96.9% valid responses for children. For the non-illusion trials (1F0B, 1F1B, 2F0B, 2F2B), the accuracy scores reflected the degree to which participants were able to accurately count the visual flash stimuli with no beeps or with a congruent number of beeps. Conversely, for the illusion trials, low accuracy scores indicated the presence of illusory perception. In fission trails (1F2B), low accuracy indicated that *more* flashes were reported than were presented, and in fusion trials (2F1B), low accuracy indicated that *less* flashes were reported than were presented.

Figure 2 shows mean accuracy scores (with 95% confidence intervals) for each stimulus type. In general, all participants responded with a high level of accuracy for all non-illusion stimuli, indicating that the visual stimuli were not ambiguous and that the visual flashes could be counted relatively easily by both children and adults. This was the case both in trials with no auditory stimulus present (1F0B and 2F0B) and in those where the number of auditory and visual stimuli were equal (1F1B and 2F2B). However, accuracy was generally reduced for both types of illusion trials (fission – 1F2B, and fusion – 2F1B) in both adults and children.

*** INSERT FIGURE 2 HERE ***

In fission illusion trials (1F2B), participants often reported more flashes than were present; in fusion illusion trials (2F1B), participants often reported less flashes than were presented. While accuracy for adults and children dropped to a similar level in fusion trials, accuracy for children dropped far more than in adults for fission trials, suggesting that children may be more susceptible to the flash-beep illusion than adults, especially in fission trials. Indeed, children reported more flashes than were presented on almost all fission illusion trials.

The significance of these effects was assessed using a mixed analysis of variance (ANOVA) with a between-subjects factor of Group [adults, children], and withinsubjects factors for Nflash [1 flash, 2 flashes], and Nbeep [0 beeps, 1 beep, 2 beeps]. There was a significant main effect of group, $F(1,50)=23.5$, $p<.001$, $\eta^2=.32$, with adults significantly more accurate than children overall. There were also significant nflash, $F(1,50)=11.8$, $p=.001$, $\eta^2=.20$, nbeep, $F(2,100) = 55.2$, $p<.001$, $\eta^2=.52$, and Nflash x Nbeep x Group interactions, $F(2,98) = 3.6$, $p=.03$, $\eta^2=.07$. Accuracy in the illusion trials compared to the corresponding non-illusion trials was examined by decomposing the three-way interaction using simple effects analysis (Howell, 2009). Pairwise comparisons with Bonferonni-corrected alpha levels are reported throughout. In one-flash trials, both adults, $F(2,49)=31.9$, $p<.001$, and children, $F(2,48)=98.5$, $p<.001$, had significantly lower accuracy scores on fission illusion trials compared with both non-illusory single-flash trials, although the extent of the drop in performance was significantly larger for children than adults, $F(1,48)=28.2$, $p<.001$.

In two-flash trials, there was again a significant drop in accuracy for both adults, $F(2,49)=12.5$, $p<.001$, and children, $F(2,49)=25.8$, $p<.001$, for the fusion illusion trials compared to both of the non-illusion two-flash trials. However, there was no significant difference in accuracy between adults and children in the fusion illusion trials.

Thus, the fission illusion, originally reported by Shams et al (2000), was found to be present in children, and to a significantly greater degree than in adults. The corresponding fusion illusion, first reported by Andersen et al (2004), was also found to be present in children, but not to a significantly greater degree than in adults.

Flash-beep – reaction times

In order to further explore the difference between fission and fusion trials in adults and children, reaction times for all six stimulus types were examined. Reaction times for correct and incorrect responses were collected. In the non-illusion trials, only correct responses were analysed. However, in the illusion trials, incorrect responses are also of interest, as they are linked to reports of illusory perception. The reaction time data were thus split into illusion trials (1F2B, 2F1B) and non-illusion trials (1F0B, 1F1B, 2F0B, 2F2B). Mean reaction times (and 95% confidence intervals) for each stimulus type are shown in Figure 3. Consistent with the Pegboard results, children were consistently slower to respond than adults in the non-illusion trials (Figure 3A). However, as can be seen in Figure 3B, adults appeared to lose their expected reaction time advantage in the illusion trials, except in incorrectly-responded fusion-illusion trials (i.e., when they reported the illusion).

*** INSERT FIGURE 3 HERE ***

For non-illusion trials (Figure 3A), a Group [adults, children] x Nflash [1 flash, 2 flashes] x Nbeep [0 beeps, 1 beep, 2 beeps] mixed ANOVA showed that adults were faster overall than children, $F(1,50)=15.5$, $p<.001$, $\eta^2=.24$. The only other significant effect was nbeep, $F(1,50)=21.0$, $p<.001$, $\eta^2=.30$, with significantly faster reaction times when a beep was present compared to no beep. No other main effects or interactions were significant, indicating that, for both adults and children, reaction times were fairly similar whether a single or double flash was presented. As a whole, however, participants were significantly faster when flashes were presented along with a congruent number of beeps.

In illusion trials (Figure 3B), a Group [adults, children] x Stimtype [fission, fusion] x Response [correct, incorrect] repeated-measures ANOVA showed no main effect of group, $F(1,43)=.04$, $p=.8$, indicating that children and adults showed similar reaction times in illusion trials overall. However, there was a significant Group x Stimtype x Response interaction, $F(1,43)=4.5$, $p=.04$, $\eta^2=.10$. Simple effects analysis revealed that while reaction times to incorrectly-responded stimuli for adults and children did not differ in the fission trials, adults were significantly faster, $F(1,43)=7.1$, $p=.01$, than children when they responded incorrectly to fusion stimuli.

By comparing reaction times across all stimuli in panels A and B in Figure 3, it is also clear that while children appear to respond with roughly similar overall reaction times in illusion and non-illusion trails, adults are generally slower in illusion trials compared to non-illusion trials. Reaction times for all illusion and non-illusion stimuli were averaged together, and a Group [adults, children] x Illusion [illusion, no-illusion] repeated-measures ANOVA revealed a significant Group x Illusion interaction, $F(1,50)=16.4$, $p<.01$, $\eta^2=.25$. Simple effects analysis indicated that while there were no differences in reaction times between illusion and no-illusion trials for children, adults were significantly slower in illusion trials than no-illusion trials, $F(1,50)=38.3$, $p<.01$.

Flash-beep – correlations

To determine if there was any relationship within each group between age and performance on the illusion task, Pearson correlations were calculated between age and the accuracy scores and reaction times for all stimulus types. No significant correlations were found between age and any of these variables, for both adults and children. A representative example is given in Figure 4 for accuracy scores in the two illusion stimuli. Although adults and children showed very different results, there was no relationship within each group between age and accuracy for either the fission or fusion illusion trials.

*** INSERT FIGURE 4 HERE ***

In order to explore any relationship between accuracy, reaction times, and Purdue Pegboard scores, Pearson correlations were also calculated between accuracy scores for fission and fusion stimuli, the pegboard scores for the right hand, and reaction times for correct and incorrect responses for both illusion stimuli. Table 2 shows the matrix of correlations performed with accuracy scores. The Purdue Pegboard scores did not significantly correlate with any accuracy or reaction time variables in either adults or children, indicating that manual dexterity does not have a differential effect for different stimulus combinations in either group. The Pegboard correlations are not included in the table to conserve space. Note that the N values for correlations involving reaction times vary between conditions. This is a consequence of examining reaction times for both correct and incorrect responses – participants with 100% or 0% accuracy did not submit incorrect- or correct-response reactions times, respectively. In adults, accuracy for fission and fusion trials was significantly correlated, with those participants reporting the fusion illusion also reporting fission illusions, and vice versa. Children showed no such relationship. The only significant correlations between accuracy scores and reaction times were in adults – adult participants who had high accuracy for both fission and fusion stimuli had slower reaction times for correct responses to fusion stimuli.

*** INSERT TABLE 2 HERE ***

Discussion

In the current study, adults and children were asked to count how many flashes they saw during the presentation of an auditory-visual illusion that indexes the integration of auditory and visual information. One or two flashes were presented, along with zero, one, or two beeps. The main finding was that children, performing the same task as adults, reported significantly more *fission* illusions than adults, where the presentation of two beeps caused a single flash to be reported as two. Children also reported more *fusion* illusions than adults, where a single beep caused a double flash to be reported as one, but the difference was not significant. Despite children reporting significantly more fission illusions than adults, there was no correlation within either group between age and accuracy on either fission or fusion trials. These results show that the mechanisms that integrate auditory with visual information, giving rise to the flash-beep illusion, do not follow a linear developmental trend with age in this group of normally developing children.

Both adults and children reported fission and fusion illusions on trials where either more or fewer beeps than flashes were presented. Adults reported illusions on approximately 50% of trials, a figure comparable with many other studies using the flash-beep illusion paradigm (Andersen et al., 2004; Courtney et al., 2007; Innes-Brown & Crewther, 2009; Meylan & Murray, 2007; Shams et al., 2000, 2002). However, children reported far more fission illusions than adults. In the flash-beep illusion, the accuracy of counting a quickly flashed visual stimulus decreases if an incongruent number of beeps are presented at the same time. There have been many behavioural and neuro-imaging studies suggesting that this effect occurs as a result of the integration of auditory cues with visual information at a relatively low level in the brain, at least at the level of the primary visual cortex (Mishra, Martinez, & Hillyard, 2008; Mishra et al., 2007; Shams, Iwaki, Chawla, & Bhattacharya, 2005; Shams et al., 2001; Watkins et al., 2007; Watkins et al., 2006). There is also psychophysical evidence suggesting that the phenomenon is the result of an illusory visual percept, rather than the modification of response biases (McCormick & Mamassian, 2008). In the current study, we have shown that children appear to integrate auditory and visual information more frequently and less selectively in the flash-beep illusion task than adults, leading to more illusory perceptions when incongruent auditory-visual stimuli are presented.

To our knowledge, there is only one previous study examining the flash-beep illusion in children (Tremblay et al., 2007). In that study, children in three age ranges (5-9, 10-14, and 15-19) performed flash-beep illusion as well as McGurk illusion tasks. The authors found that the youngest group of children reported significantly fewer McGurk illusions than either of the older groups. In the flash-beep task, however, no differences were found between the groups, although all the age groups did show significant fission and fusion illusions. The authors suggested that different mechanisms underly the flash-beep illusion, which was already mature in their sample, compared with the mechanisms underlying the McGurk effect, which was still developing. In the present study, it was not possible to divide the children into three equally-sized age groups in order to make a direct comparison; however, no correlation was found within the child group between age and either accuracy or reaction time in the flash-beep task, and examination of the raw data (see Figure 4) does not suggest any linear, bimodal, or otherwise non-linear relation between age and accuracy. The results are thus consistent with those found by Tremblay et al., and the accuracy scores for the children in their study correspond well to those found in the current study. The current results also support their conjecture that the mechanisms underlying the two illusions are likely different. However, as shown in the current study, a group of adults performing the same task reported far fewer fission illusions than children, suggesting a different interpretation: that the mechanisms underlying the illusion are still developing.

As the main measure of illusory perception was a reduction in the accuracy of counting visual flashes, it was important to ensure that the reduced accuracy shown by children in illusion trials was not simply reflective of overall reduced accuracy in perceiving single and double flashes. In addition to the illusion trials, accuracy scores were recorded for single and double flash trials with either no concurrent beeps, or with a congruent number of beeps. In these control trails, adults were generally more accurate than children. However, although the accuracy of adults was approximately 13% higher than children in the 1F0B control trials (where the difference was largest), adult accuracy was 34% higher in the 1F2B illusion trials. Thus, although adults were more accurate overall, the difference was far more pronounced in the illusion trials. To fully control for this effect, a future study could equalise the task difficulty by the use of degraded flash stimuli for the adults.

Nevertheless, children's accuracy rates were still high in the unisensory control trials – over 75% for one-flash trials and over 80% for two-flash trials, indicating that children had little difficulty in responding correctly to the visual stimulus when it was presented alone. Similarly, congruent multisensory trials were presented, where the number of beeps was the same as the number of flashes. In these trials, both adults and children were more accurate still, with all scores above 80%. It is well known that humans can detect multisensory combinations of signals more quickly and accurately than either of the signals presented alone. This facilitation of accuracy and reaction time is called the redundant signal effect, and has been extensively investigated in adults (Gielen, Schmidt, & Van den Heuvel, 1983; Hecht, Reiner, & Karni, 2008; Molholm, Ritter, Javitt, & Foxe, 2004). These studies have generally used Miller's inequality (Miller, 1982) to show that reaction times to multisensory stimuli are faster than can be predicted by "race" models (Raab, 1962), in which the faster sense simply initiates the motor response. Instead, they suggest co-activation models, where the signal from each sense is integrated at an early stage in order to produce a faster response. Barutchu, Crewther, & Crewther (2009) and Barutchu et al (2010) used this method to show that although reaction times of children were generally faster with multisensory compared to unisensory stimuli, children up to 12 years of age were not as fast as adults and did not show the reaction time advantage that would be expected under a co-activation model. As in the present study, the level of multisensory facilitation observed did not correlate with either age or motor reaction times. In a relatively early study, Hulme, Smart, Moran & Raine (1983) also found no relationship between visual-kinaesthetic integration and motor skill development. In the current study, both children and adults were significantly faster in response to audio-visual than purely visual stimuli. However, an auditory-only stimulus was not included. This fact, and the very different task demands, makes it difficult to compare the results directly with studies explicitly designed to test Miller's inequality. In any case, the participants in the current study showed significant benefits both in terms of accuracy and reaction times in response to visual stimuli when congruent audio-visual stimuli were presented compared to visual alone. Children had lower accuracy scores than adults in the visual-alone and congruent multisensory trails, and as expected from the lower Pegboard scores, were significantly slower overall. However, both groups showed high levels of accuracy overall, were significantly faster in congruent multisensory trials, and had no problems distinguishing a single flash stimulus from a double flash stimulus. Taken together, these results further support the conjecture that MSI does not follow a linear developmental trajectory with either age or the development of motor coordination.

As well as reporting fewer illusions overall, adults had significantly faster reaction times than children in the unisensory and congruent multisensory control trials. In illusion trials, however, the adults maintained higher accuracy levels than the children, but lost the reaction time advantage and responded more slowly than in the control trials. This slowing in the illusion trials was especially apparent for trials in which a correct response was made (i.e. the illusion was not reported). In adults, there was also a significant negative correlation between accuracy and reaction time, but only for *fusion* stimuli with a *correct* response. This may indicate that responding correctly in the presence of an incongruent number of beeps requires the suppression of an automatic integrative process, thereby slowing the final response. The ability to inhibit pre-planned responses has been shown to develop slowly, with improvements from the ages of 6 to 20 (Band, van der Molen, Overtoom, & Verbaten, 2000), and these improvements have been linked to the development of prefrontal cortex (Tamm, Menon, & Reiss, 2002). In the current study, the automatic integration of auditory with visual information may have been unsuccessfully inhibited in children. In the fusion trials with an incorrect response, adults were also significantly faster than the children, again suggesting a failure in inhibition.

A further difference between the adults and children in the present study was in relation to the pattern of results for fission and fusion stimuli. Although children reported significantly more fission illusions than adults, the difference between groups was less clear and not statistically significant for fusion stimuli. In addition, there was a significant positive correlation between accuracy scores for each illusion trial type in adults, but not children – while adults who reported many fission illusions also reported many fusion illusions, there was no such relationship in children. One possibility for this difference is due to the reliability of each sense modality in the task of distinguishing between rapid events. In their original studies, Shams et al. (2000, 2002) only reported fission illusions – they found that an illusion occurred only when the number of beeps exceeded the number of flashes and not vice versa. The well-established "modality appropriateness" hypothesis (Welch & Warren, 1980) thus could not explain their results. According to this theory, the number of beeps should always dominate over the number of flashes, as audition provides more accurate temporal information than vision. However, this did not appear to be the case in Shams et al. (2000, 2002), and the authors proposed instead the "discontinuity hypothesis" – that the discontinuous stimulus in one modality alters the percept of the continuous stimulus in the other modality. The present results indicate that the auditory stimulus, whether it was continuous or discontinuous, dominated, or at least altered, the visual percept. Hence, the results are more supportive of the modality appropriateness hypothesis.

In the current study, the effect of the discontinuous stimulus (the double beep) was stronger in children than adults. These results are in agreement with some early data indicating that infants show auditory dominance when presented with an audio-visual checkerboard/beep stimulus. Infants are more responsive to changes in the rate of the beep stimulus than the spatially static flashing checkerboard (Lewkowicz, 1988a, 1988b) When the checkerboard is moving, however, the stimulus is spatially-dynamic, audition is no longer the more appropriate sense, and the responses are no longer dominated by the auditory stimulus (Lewkowicz, 1992). However, as Andersen et al. (2004) have also found, discontinuous auditory stimuli (i.e. the double beep in fission illusion trials) had a stronger effect on the final visual percept than continuous auditory stimuli (the single beep in fusion illusion trails), and Andersen et al. point out that it is likely that modality appropriateness and stimulus discontinuity are both factors that combine to influence the dominance of each modality.

The results from the present study are generally in agreement with previous research showing that the ability to appropriately integrate information from multiple senses is not fully developed until late in childhood. This finding is broadly consistent with neurophysiological studies in cat (Wallace, Carriere, Perrault, Vaughan, & Stein, 2006) and monkey (for review see Stein, Stanford, & Rowland, 2009) which have characterised the development of multisensory neurons in the midbrain (superior colliculus - SC) and cortex (anterior ectosylvian sulcus – AES). These studies have found that although multisensory neurons in the SC exist at birth in monkeys, or soon after in the cat, they have very large receptive fields that narrow with age, and although they respond to multiple sensory inputs, many do not have the ability to *integrate* these inputs (Wallace & Stein, 1997). As these receptive fields narrow with post-natal development, it is possible that integrative abilities become more selective. The ability of SC neurons to integrate inputs from multiple senses is slow to develop, and is guided by cortical input from the AES, an area of cortex which is slower to develop than the SC (Jiang & Stein, 2003; Stein, Wallace, Stanford, & Jiang, 2002). This AES-SC circuit is thought to be the mechanism by which experience and learning adapts multisensory responses in the SC to environmental pressures (Stein et al., 2009). These findings fit with the idea that while some multisensory abilities, such as intensity matching (Lewkowicz & Turkewitz, 1980), audio-visual rhythm detection (Bahrick & Lickliter, 2000, 2004) and the detection of temporal equivalence in the form of speech onsets and offsets (Lewkowicz, 2010; Lewkowicz et al., 2010) can be present from birth, while other abilities, particularly those that require the integration of multiple sensory inputs, can require a prolonged developmental period. The stream-bounce illusion, for example, does not emerge in infants until six months of age (Scheier et al., 2003a), and spatial orienting responses do not show multisensory facilitation until 8 months of age (Neil, Chee-Ruiter, Scheier, Lewkowicz, & Shimojo, 2006). Facilitation of size and orientation judgements by visio-haptic stimuli occurs even later, at between 8-10 years of age (Gori et al., 2008), and children as old as 11 years do not show mature facilitation of reaction times to auditory-visual stimuli (Barutchu et al., 2010). The current study extends this time-line by showing that a group of children aged 8-17 reported significantly more fission illusions in the flash-beep illusion task.

Finally, it is important to note some major differences of approach between studies looking at multisensory facilitation and the current study. Overall, these studies have suggested that the ability to gain behavioural *advantage* from congruent multisensory stimuli does not mature until at least late childhood. The current study, in contrast, was focussed on incongruent multisensory trials, that, due to the integration of information from each sense, gave rise to perceptual illusions. Hence, a *reduction* in accuracy was the main index of multisensory integration. Although children in the current study did not show mature performance in the multisensory illusion task, the results suggested that this was due to more, but *less selective,* integration of auditory with visual information, resulting in more illusory percepts. There are a multitude of possible neural mechanisms underlying the ability to integrate sensory information (Cappe, Rouiller, & Barone, 2009), and these mechanisms are likely to mature at different rates. In the context of the flash-beep illusion task, maturation of the sensory and multisensory pathways appears to result in the ability to more selectively integrate auditory information with visual information, resulting in less perceptual errors as development progresses. In the non-illusory control trials, it was also shown that both adults and children showed the expected facilitation of accuracy and reaction times scores to congruent multisensory compared to visual-alone stimuli.

Conclusion

This study has shown that the ability to selectively integrate auditory and visual information, as indexed by an auditory-visual illusion, is not mature in a group of 8-17 year-old children. In the flash-beep illusion task, children reported significantly more fission illusions than adults. Reports of the illusion were not correlated with age in either children or adults, suggesting a shift in development of this process at an age beyond the range included in this study. To further understand how these abilities develop, it may be necessary to test a variety of multisensory abilities in both adults and children over a wider range of ages. The current study is supportive of recent research suggesting that although multisensory abilities such as matching and comparison can develop very early in infancy, the ability to appropriately integrate sensory information in order to facilitate or alter sensory experience may require a much more extended period of development.

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Table 1

Means, standard errors of the mean, and t-test outcomes for Purdue Pegboard Scores.

	Adults	**Children**	**t-test**
Pegboard-Right (SD)	16.0 (2.3)	13.2 (2.1)	$t(46)=4.5$ *
Pegboard-Left (SD)	15.1 (1.5)	12.7 (2.0)	$t(46)=4.7$ *
Pegboard-Both (SD)	12.9 (1.4)	10.8 (1.5)	$t(46)=4.9$ *

Note. Pegboard scores are the number of pegs inserted in 30 seconds;

Standard errors of the mean are given in parentheses; * $p < .05$ (two-tailed)

Table 2

Correlations Between Accuracy Scores for Fission and Fusion Stimuli, Purdue Pegboard Scores, and Reaction Times (RT) for Correctly and Incorrectly Responded Stimuli.

		Accuracy – Adults		Accuracy - Children	
		Fission	Fusion	Fission	Fusion
Fission Accuracy	*r*		**.53***		.11
	N		22		30
Fission RT(correct)	*r*	-.15	-.29	.12	.12
	N	21	21	30	30
Fission RT (incorrect)	*r*	.17	.14	-.06	-.34
	N	21	21	30	30
Fusion RT (correct)	*r*	**-.45** *	**-.85** **	-.12	-.25
	N	19	19	29	29
Fusion RT(incorrect)	*r*	-.20	-.004	-.07	-.20
	N	21	21	30	30

* $p < .05$ (2-tailed)
** $p < .01$ (2-tailed)

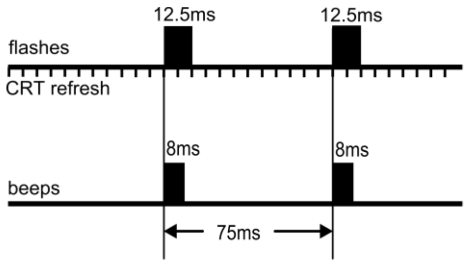

Figure 1. Flash beep stimulus timing. Shown is an example of a 2-flash, 2-beep (2F2B) trial.

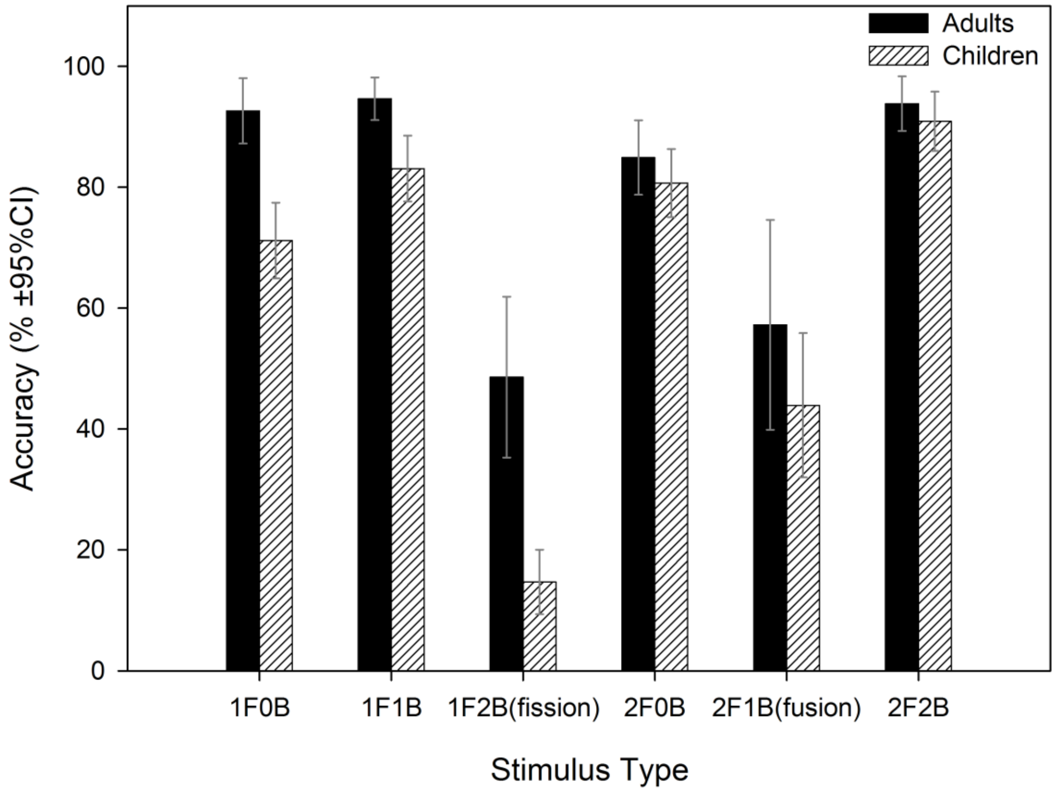

Figure 2. Mean accuracy measures and 95% confidence intervals (CI) for each stimulus type for adults and children.

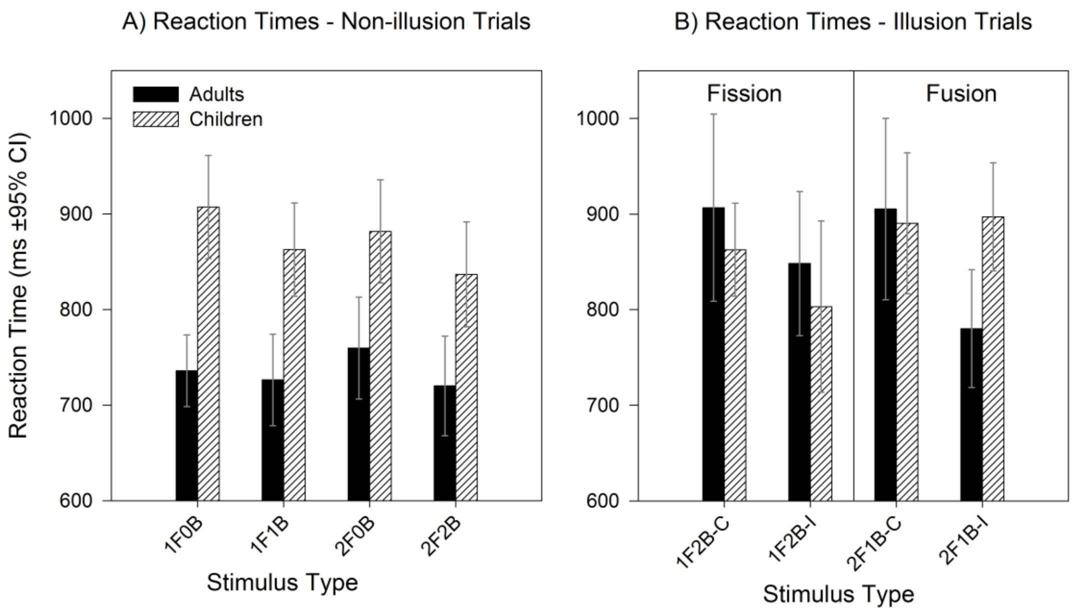

Figure 3. Reaction times (ms) and 95% *CIs* for non-illusion (A) and illusion (B) trials. Reaction times for correct responses only are shown in A. In B, reaction times for correct (C) and incorrect (I) responses are shown separately.

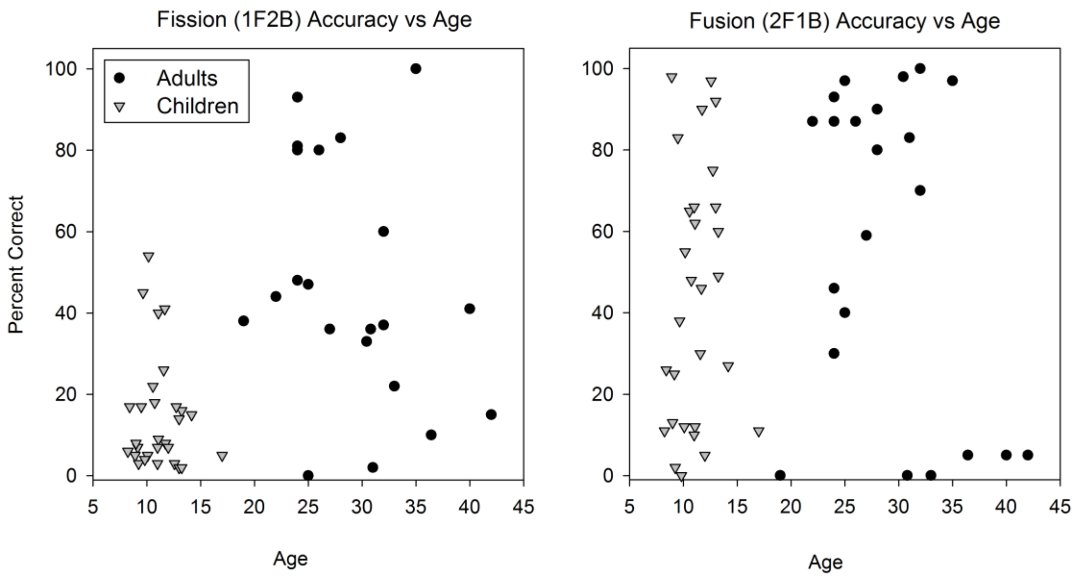

Figure 4. Scatter plots showing raw accuracy scores for adults and children to 1F2B (fission) and 2F1B (fusion) stimuli.