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Developmental changes in audiotactile event perception

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ABSTRACT

The fission and fusion illusions provide measures of multisensory integration. The sound-induced tap fission illusion occurs when a tap is paired with two distractor sounds, resulting in the perception of two taps; the sound-induced tap fusion illusion occurs when two taps are paired with a single sound, resulting in the perception of a single tap. Using these illusions, we measured integration in three groups of children (9-, 11-, and 13-year-olds) and compared them with a group of adults. Based on accuracy, we derived a measure of magnitude of illusion and used a signal detection analysis to estimate perceptual discriminability and decisional criterion. All age groups showed a significant fission illusion, whereas only the three groups of children showed a significant fusion illusion. When compared with adults, the 9-year-olds showed larger fission and fusion illusions (i.e., reduced discriminability and greater bias), whereas the 11-year-olds were adult-like for fission but showed some differences for fusion: significantly worse discriminability and marginally greater magnitude and criterion. The 13-year-olds were adult-like on all measures. Based on the pattern of data, we speculate that the developmental trajectories for fission and fusion differ. We discuss these developmental results in the context of three non-mutually

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exclusive theoretical frameworks: sensory dominance, maximum likelihood estimation, and causal inference.

Introduction

The perceptual system tends to integrate sensory signals from different modalities when they are likely originating from the same event (Shams & Beierholm, 2010; Welch & Warren, 1980). Such multisensory integration allows us to perceive, interact with, and navigate through the world more precisely (Gori et al., 2008; Nardini et al., 2008; see Ernst & Bülthoff, 2004, for an early review). Within this context, the integration of audition and touch provides an important perspective. More specifically, touch may provide a scaffold for the development of the other spatial senses because of its direct and proximal perception. However, touch and especially its interactions with audition are underrepresented in developmental psychology (Bremner & Spence, 2017). Thus, to help fill that gap, we examined audiotactile integration across middle childhood.

The somatosensory sense develops during gestation (~1–2 months; see Bremner et al., 2012), receiving stimulation as the fetus bumps into itself, the uterus, or the umbilical cord (e.g., Hooker, 1958). This is long before the auditory and visual systems become functional and receive stimulation (~7 months gestational age and after birth, respectively). Near birth, the fetus shows sensitivity to cross-modal auditory–vibrotactile stimulation (Kisilevsky & Muir, 1991), whereas functional visuotactile connections appear to develop postnatally (Begum Ali et al., 2015; Held et al., 2011; Maurer et al., 1999). From birth onward, multisensory integration refines and follows unique trajectories depending on the type of task (e.g., Gori et al., 2021) and modality pairings (e.g., Stanley et al., 2019, Fig. 3). Most often, adult-like performance is reached around middle to late childhood (see Burr & Gori, 2012), but development may be more protracted when one of the modalities is touch (e.g., Gori et al., 2008; Petrini et al., 2014; Scheller et al., 2021; Stanley et al., 2019).

The few developmental cross-modal studies specifically examining the integration of hearing and touch find a late maturity. Although there are no studies yet examining the development of integration with passive tactile perception, two studies examined the integration of audition and active haptic size discrimination (Petrini et al., 2014; Scheller et al., 2021). Using a child-friendly design, participants actively patted a comparison ball either before or after patting a standard ball; their task was to indicate which was larger. On bimodal trials, a prerecorded sound of a ball hitting a table was presented. The sound was either size congruent (the loudness of the sound corresponded to the size of the comparison ball) or size incongruent (the size of the comparison ball and the loudness of the sound averaged to match the size of the standard). Using maximum likelihood estimation, these authors determined the relative reliability of the auditory and haptic cues and determined if and when observers combine multisensory cues optimally. Scheller et al. (2021) demonstrated that adult-like optimal integration emerged between 13 and 15 years of age. This appears to be the latest age of maturation reported to date in the developmental literature for all possible pairings of cross-modal integration (see Scheller et al., 2021, Fig. 9). This late development of audiohaptic integration may have to do with the active nature of this task; it may index processes beyond simple touch, including proprioception, efference copy, attention, and other higher-order cognitive processes such as the prior probability of cue combination (see Discussion).

Stanley et al. (2019) charted the development of simultaneity perception for audition and passive touch. Although audiotactile integration was not measured in this study, simultaneity perception provides one of several cues that the perceptual system relies on to support multisensory integration (see Chen et al., 2016, for discussion). In a cross-modal simultaneity judgment task, participants are presented with two stimuli from different modalities either coincidently or separated by one of several stimulus onset asynchronies (SOAs); participants' task is to report whether the two stimuli were simultaneous or not (Chen et al., 2016, 2018; Machulla et al., 2016; Stone et al., 2001; Zampini et al., 2005). Based on the proportion of simultaneous responses at each SOA, the temporal window of simultaneity is estimated. With the pairing of audition and passive tactile stimulation, Stanley et al. (2019) demonstrated an adult-like maturity by 11 years of age; the same age as visuotactile (Chen et al., 2018), and approximately two years later than for audiovisual (Chen et al., 2016) simultaneity perception. Although both Stanley et al. (2019) and Scheller et al. (2021) agree that interactions between audition and touch mature late, clear questions emerge as to when integration between audition and passive tactile touch becomes adult-like and whether it is comparable to the age of maturation for audiohaptic integration.

The fission and fusion illusions provide strong measures of multisensory integration. These illusions occur when conflicting numbers of stimuli are presented passively to two separate modalities close in time. First described in the audiovisual domain, fission occurs when a single visual flash is perceived as two distinct flashes when paired with two auditory stimuli (Shams et al., 2000, 2002), whereas fusion occurs when two visual flashes are perceived as a single flash when paired with a single auditory stimulus (Andersen et al., 2004). Mounting evidence suggests that these two illusions are driven by different mechanisms (see Bolognini et al., 2011, 2016; Chen et al., 2017; Mishra et al., 2007, 2008; but see Hirst et al., 2020), including the finding of different developmental trajectories (Innes-Brown et al., 2011). It is suggested that fusion is influenced by decisional factors more than fission, and the latter appears to be more perceptual in nature (Chen et al., 2017). Regardless, these illusions have been demonstrated for audiotactile pairings in which audition influences the perception of touch (sound-induced tap illusion) (Bresciani et al., 2005; Bresciani & Ernst, 2007; Bresciani et al., 2008; Hötting & Röder, 2004; Wozny et al., 2008). The reciprocal tap-induced sound illusion, to our knowledge, has only been reported in one study (Bresciani & Ernst, 2007), which required careful balancing of the relative reliabilities of the auditory and tactile signals.

Predictions regarding when audiotactile integration becomes adult-like are difficult because of the paucity of relevant data; there are few studies of audiotactile integration and even fewer of its development (e.g., Bremner & Spence, 2017; Occelli et al., 2011). Given the early development of touch (Bremner & Spence, 2017) and hints of integration occurring with audition prenatally (Kisilevsky & Muir, 1991), one might expect audiotactile integration to mature earlier than other modality pairings. However, our own work on the perception of multisensory simultaneity found later development associated with touch; as mentioned previously, audiovisual perception was adult-like by 9 years of age, but visuotactile and audiotactile perception was adult-like by 11 years of age (Chen et al., 2016, 2018; Stanley et al., 2019). Hence, we predicted that audiotactile fission and fusion illusions would mature between 9 and 13 years of age. Note that we could not rule out an even later age of maturation based on the results from the audiohaptic size discrimination task (Petrini et al., 2014; Scheller et al., 2021).

In the current study, we measured developmental changes for the integration of audition and passive touch as indexed by the fission and fusion illusions. Given that fission and fusion plausibly occur at different levels of processing—fission appears to be more perceptual, whereas fusion appears to be more influenced by decisional factors (Chen et al., 2017)—we predicted an earlier maturation for fission than for fusion. Each participant completed both sound-induced tap and tap-induced sound tasks. On each trial, either one or two target taps (or sounds) were presented concurrently with zero, one, or two distractor sounds (or taps). Participants reported the number of taps (or sounds) perceived. We measured the magnitude of each illusion based on accuracy in the conflict conditions; the more errors made, the stronger the illusion. In addition, we applied a signal detection analysis to disentangle the influence of distractors on perceptual discriminability from response criterion when reporting the number of taps (or sounds). Our main question concerned when performance became adult-like. As such, we compared each group of children against the adult control group separately for each illusion. In addition to expecting all groups to demonstrate measurable fission and fusion illusions, we also expected children to demonstrate larger illusions than adults (e.g., Adams, 2016). All analyses reflect these *a priori* planned directional hypotheses (see “Analysis” section in Method for details).

Method

Participants

In total, 20 participants were tested from each of four age groups: 9-year-olds (M_{age} = 9.1 years, SD = 0.1), 11-year-olds (M_{age} = 11.1 years, SD = 0.1), 13-year-olds (M_{age} = 13.0 years, SD = 0.1), and adults (M_{age} = 20.0 years, SD = 1.9). Based on past research (Stanley et al., 2019), we set the recruitment criterion to ±3 months for the three groups of children. All groups had an equal split of male and female participants (defined by sex at birth). All participants were right-handed and reported normal auditory and tactile acuity. As is standard in our lab, visual ability was assessed using the Randot test of stereoacuity in which a minimum of 40 s of arc was required to participate.

An additional 18 participants were tested but excluded because they did not meet the minimum inclusion criteria in the practice blocks (2 nine-year-olds and 1 thirteen-year-old), they did not reach 80% correct on the catch trials (6 nine-year-olds and 4 eleven-year-olds), they failed the vision screening (1 thirteen-year-old), or the tap machine malfunctioned (2 nine-year-olds and 2 eleven-year-olds).

Children were recruited from a database of parents who, at the time of their children's birth, consented to be contacted about participation in developmental research. Parents provided written consent for their children to participate, and children provided verbal assent to participate after being read a child-friendly consent form. In exchange for participation, children were rewarded with a book or toy and a junior scientist certificate. Adult participants were recruited from the undergraduate study pool at McMaster University and received a course credit in exchange for their participation. This study was approved by the McMaster Research Ethics Board and adhered to the Tri-Council Statement on Ethical Conduct of Research Involving Humans (TCPS2; Canada).

Apparatus and stimuli

The auditory stimulus was a 10-ms peak-to-peak white noise burst with a flat amplitude envelope and 2-ms onset and offset ramping (henceforth referred to as a *beep*). The beeps were presented via Sennheiser HDA-200 (closed-ear) headphones at 107 dB SPL (measurements obtained with Brüel & Kjær artificial ear Type 4152 and Brüel & Kjær sound level meter Type 2270). White noise was played

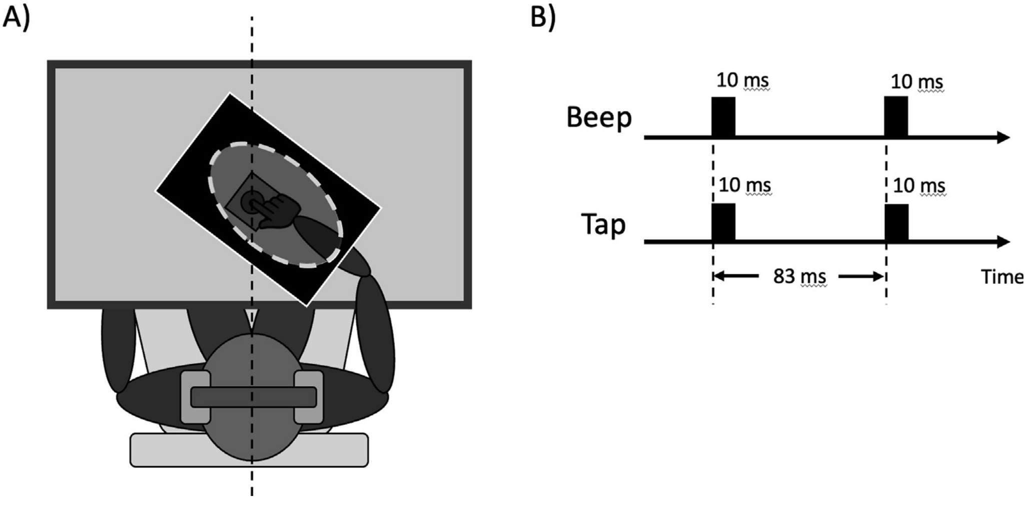

Fig. 1. Experimental setup and a sample trial. (A) Overhead view of a participant seated facing the table. Headphones were used to present the auditory stimuli, and a tactor mounted in a sound-attenuating box delivered the tactile stimulus to the right index finger. The tactor was aligned with the participant's midline. (B) The temporal profile of a trial consisting of two beeps and two taps with their onsets separated by an 83-ms delay.

in free field at 73 dB to reduce the possibility of perceiving extraneous noise emitted by the tactile stimulators. The tactile stimulus was generated from below the participant's hand comprising a 10-ms tap to the right index finger (Fig. 1A). The taps were generated by one of two custom-built tactile stimulator machines that were mounted in a noise-attenuating box. These machines indented the skin by approximately 3 mm, which to an observer was perceived as a light touch. The original machine used a dull metal pin mounted on a mechanical solenoid. This machine was replaced approximately halfway through data collection when it began missing trials; this change did not affect the results (see online supplementary material for additional details and analyses). The replacement machine was an electromagnetic solenoid mounted in a wooden block. When activated, a dull plastic peg protruded from the base and tapped the finger. In total, 8 nine-year-olds, 12 eleven-year-olds, 15 thirteen-year-olds, and 16 adults were tested on the original machine.

Both the auditory and tactile stimuli were generated and temporally controlled by MATLAB (MathWorks, Natick, MA, USA) with the Psychtoolbox-3 package (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997) installed on an Apple Mac Mini. All timings were verified with an oscilloscope. The apparatus and stimuli were identical to those used in Stanley et al. (2019) that measured audiotactile simultaneity perception.

Design

The experiment consisted of two tasks; one task measured the sound-induced tap illusion, and the other task measured the tap-induced sound illusion. Each participant completed both tasks in a counterbalanced order.[1] The tap-induced sound task revealed only a weak fission illusion and no fusion illusion, along with no developmental changes. These results did not provide any meaningful theoretical contributions, and as such were excluded from the main body of this article (see supplementary material for methods and results).

Sound-induced tap illusions

There were four types of trials: unimodal, congruent, incongruent, and catch. A unimodal trial consisted of either one tap (1T0B) or two taps (2T0B). A congruent trial was either a single tap presented simultaneously with a single beep (1T1B) or two taps presented simultaneously with two beeps (2T2B). The configurations of the two types of incongruent trials consisted of different numbers of taps and beeps: one tap with two beeps (1T2B) or two taps with one beep (2T1B). The fission illusion occurred in the 1T2B condition when two taps were reported. The fusion illusion occurred in the 2T1B condition when a single tap was reported. The first tap and beep were always presented simultaneously. The second stimulus, if presented, occurred 83 ms after the onset of the first stimulus (see Fig. 1B) (delay based on previous work; see Chen et al., 2018).

Catch trials were included to determine whether the fission and fusion illusions were truly a product of auditory–tactile integration. These trials contained identical stimuli as incongruent trial types (i.e., 1T2B; 2T1B); however, the beep(s) preceded the tap(s) by 300 ms. This time value of 300 ms was chosen because it is beyond the simultaneity window in which audiotactile events are judged to have occurred together (Stanley et al., 2019). Hence, if audiotactile fission and fusion are indeed the products of integration, then we expected no illusions in the catch trials. Inclusion of these catch trials also served two additional purposes: firstly, it ensured that participants were engaged with the task, and secondly, that participants were responding to the correct (i.e., target) modality. Participants were excluded if their accuracy on the catch trials fell below 80%.

There were 140 trials divided across five blocks of 28 trials. In each block, there were eight unimodal trials (4 1T0B and 4 2T0B), eight congruent trials (4 1T1B and 4 2T2B), and eight incongruent trials (4 1T2B and 4 2T1B), plus four catch trials (2 1T2B and 2 2T1B), presented in a completely random order.

[1] Inclusion of the factor of task order did not change the pattern of significance reported below and, critically, did not interact with age (see online supplementary material).

Procedure

The participant sat at a desk in front of the tactile stimulator in a dimly lit room. The experimenter sat at the computer keyboard to the right side of the participant. The participant's right hand was inserted into the opening of the sound-attenuating box with their right index finger resting gently over a hole on the tactor device. When activated, a dull pin protruded through the hole to tap the finger. The tactile stimulator was positioned approximately 40 cm away from the participant centered at the midline of thier body. Each trial was initiated by the experimenter by pressing the Enter key. The presentation of the stimulus/stimuli occurred 500 to 1500 ms later (six random foreperiods separated by 200-ms intervals). The participant's task was to respond verbally whether they perceived one or two targets, and the experimenter keyed in the response by pressing either the 1 or 2 key. If participants missed the trial, the experimenter keyed in a 0 (zero). There was no time limit to respond.

Prior to the main experiment, participants completed four practice sessions. The first two were unimodal practice sessions: one for taps and one for beeps. These sessions ensured that participants could distinguish between one and two targets accurately. Each of these sessions included eight unimodal trials: four with one target and four with two targets. Two additional practice sessions were completed, each prior to the corresponding main task. The purpose of these sessions was to ensure that participants were responding correctly to the target modality. Each of these sessions consisted of 16 trials: eight unimodal, four congruent, and four catch. These sessions did not include any incongruent trials in which the illusion may occur. An accuracy of 85% was required in all practice tasks to participate in the main experiment.

A mandatory break intervened between the two tasks to reduce the possibility of lapses in attention (especially for children who tend to get fidgety) and, more importantly, to minimize the switch cost from one target modality in the first task to the other target modality in the second task. During the break, all participants completed the Randot stereoacuity task and the handedness task. Children were offered snacks and time to play for about 15 minutes. The average duration of the entire experimental protocol was approximately 50 minutes.

Analysis

The accuracy for each participant was first calculated as the proportion of correct responses in each condition. Missed trials (0.36% of all trials) were removed from these calculations. The mean accuracy (sound-induced tap presented in Fig. 2; analyses for both sound-induced tap and tap-induced sound provided in supplementary material) was used to compute the magnitude of illusion and used in the signal detection analysis.

The magnitude of the fission and fusion illusions was calculated for each participant by subtracting the accuracy in the incongruent condition from the accuracy in the corresponding congruent condition. Specifically, for sound-induced tap fission, the 1T2B accuracy was subtracted from the 1T1B accuracy. For sound-induced tap fusion, the 2T1B accuracy was subtracted from the 2T2B accuracy. We evaluated outliers (>3 standard deviations beyond the mean within each age group) based on the magnitude of the fission and fusion illusions, and one adult and one13-year-old were identified. To keep equal group sizes, we replaced the adult with another participant who already completed the task, but because of the COVID-19 pandemic, we could not recruit another 13-year-old.[2]

We applied an analysis based on signal detection theory to separate perceptual discriminability (d') and decisional criterion (c) (see Chen et al., 2017; McCormick & Mamassian, 2008). Responses based on multisensory processing are affected by stimulus parameters (typically held constant in an experiment), the integration mechanism itself, and decisional processes (Ernst, 2008). The advantage of using a signal detection analysis is that it separates estimates of the influence of perceptual and decisional components on participants' performance as indexed by d' and c, respectively.

[2] All analyses presented include the 13-year-old outlier; however, the pattern of results does not change when this outlier is removed.

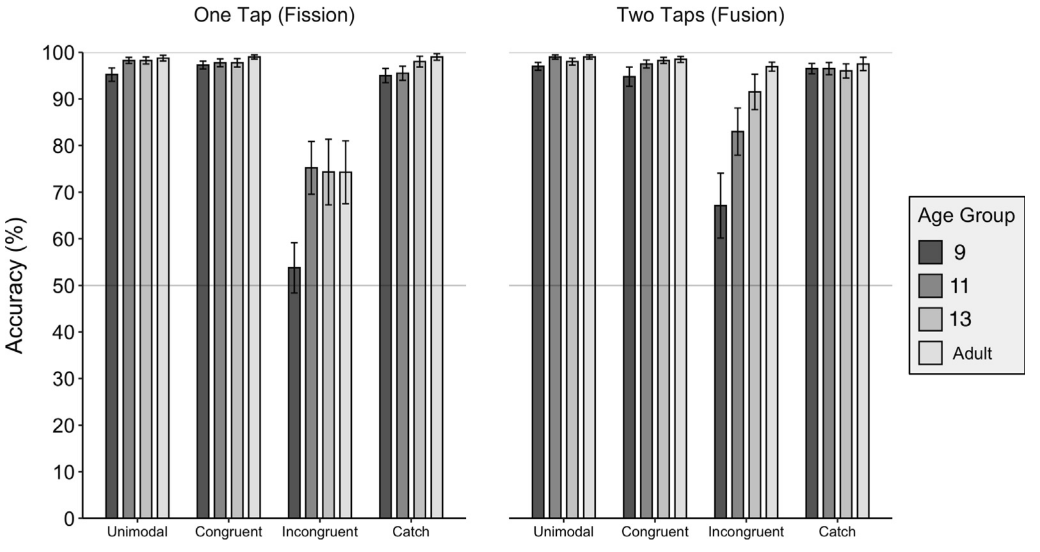

Fig. 2. Accuracy of sound-induced tap illusions. Mean accuracy of reporting the number of taps when paired with beeps in the four age groups tested is shown. The horizontal line at 50% correct represents chance performance for the unimodal, congruent, and catch conditions. The incongruent condition indexes an illusion, and thus performance at or below 50% is meaningful. Error bars are ±1 standard error of the mean.

To calculate d' and c, the accuracy data were transformed into hits and false alarms by defining the two-tap conditions as targets and the one-tap conditions as noise; thus, the proportion of hits was taken as the accuracy of performance in the two-tap conditions, and the proportion of false alarms was taken as 1 minus the accuracy (i.e., the error rate) of performance in the one-tap condition. This was done separately for the zero-beep (unimodal trials), one-beep, and two-beep conditions. The d' was computed as the z-score of hits minus the z-score of false alarms. The c was computed as -0.5 multiplied by the z-score of hits plus the z-score of false alarms. Given that the z-score for 0 or 1 is infinity, we replaced these values with half the smallest unit of measure (i.e., 1 trial of 20 in each condition). So, a value of 0 was replaced with 0.5/20 = 0.025, and a value of 1 was replaced with 1 − (0.5/20) = 0.975. For the zero-beep condition, the values index unimodal d' and c of taps; for the one-beep condition, the change from the zero-beep condition in the d' and c index the influence of the presentation of one beep, thereby associated with the fusion illusion; and for the two-beep condition, the change from the zero-beep condition in the d' and c index the influence of the presentation of two beeps, thereby associated with the fission illusion.

The fission and fusion conditions were analyzed separately; this included the measures of magnitudes of fission and fusion illusions and d' and c in the zero-, one-, and two-beep conditions. All eight dependent measures were submitted separately to a one-way analysis of variance (ANOVA) with the single between-participant factor of age (9-year-olds, 11-year-olds, 13-year-olds, or adults). Comparisons associated with an effect of age were conducted using a Dunnett's test in which each child group was compared independently to the adult (i.e., control) group; the comparisons were one-tailed because previous studies consistently demonstrate that children show larger fission and fusion illusions than adults (Adams 2016; Innes-Brown et al., 2011; Nava & Pavani, 2013). Finally, all dependent measures for each age group were compared against zero using one-sample t tests. Statistically marginal effects were reported only when below $p < .10$ and in the predicted direction. Any violations of sphericity were corrected with the Greenhouse–Geisser correction to the degrees of freedom. Effect sizes are reported as partial eta-squared (η_p^2; ANOVA) and Cohen's d (t test).

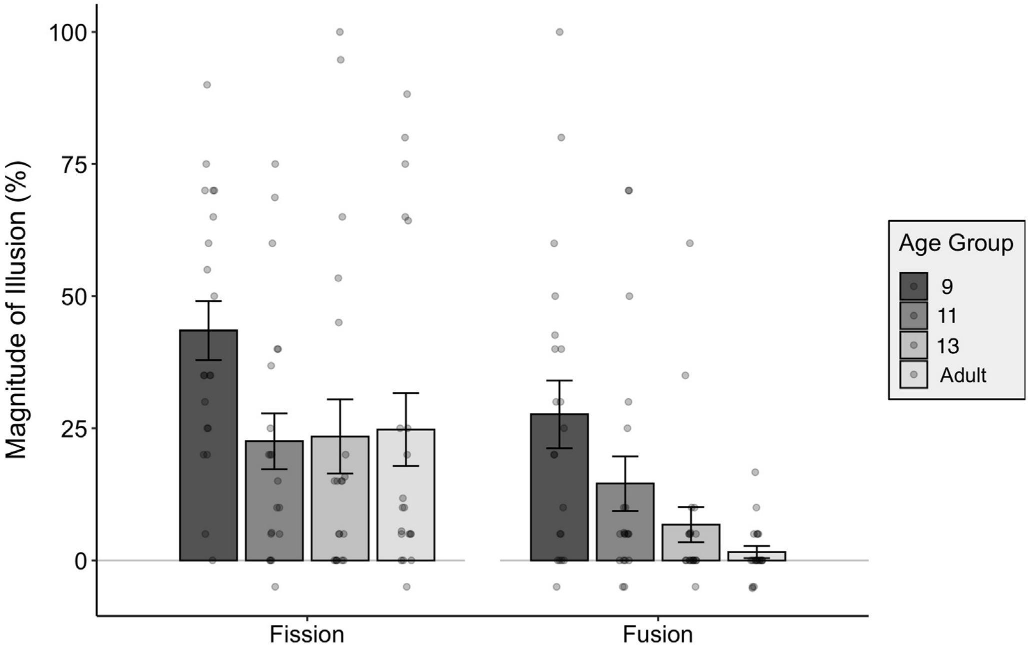

Fig. 3. Magnitude of sound-induced tap illusions. Mean magnitude of the fission (left) and fusion (right) illusions for the four age groups tested is shown. The magnitude of both illusions was calculated by subtracting the accuracy of the incongruent condition from the accuracy of the congruent condition: fission (1T1B − 1T2B) and fusion (2T2B − 2T1B). Each data point represents the performance of a participant. Error bars are ±1 standard error of the mean.

Results: Sound-induced tap illusion

Magnitude of illusion

The fission illusion was significantly different from zero for all age groups, all ts(19) > 3.34, ps < .002, ds > 0.74 (see Fig. 3). The fusion illusion was significantly different from zero for children, all ts(19) > 1.36, ps < .04, ds > 0.45, but not for adults, $t(19) = 1.36$, $p = .09$, $d = 0.30$.

The one-way ANOVA for the magnitude of fission revealed only a marginal main effect of age, $F(3,76) = 2.57$, $p = .06$, $\eta^2_p = .09$. The Dunnett's test showed that 9-year-olds had a significantly greater fission illusion than adults, $t(19) = 2.12$, $p = .047$, $d = 0.48$,[3] but 11- and 13-year-olds did not, both ts (19) < 0.25, ps > .80, ds < 0.06. The one-way ANOVA for the magnitude of fusion revealed a significant main effect of age, $F(3,76) = 6.41$, $p < .001$, $\eta^2_p = .20$. The Dunnett's test revealed that 9-year-olds showed a significantly greater fusion illusion than adults, $t(19) = 4.12$, $p < .001$, $d = 0.88$, whereas 11-year-olds showed a marginally greater fusion illusion than adults, $t(19) = 2.05$, $p = .06$, $d = 0.57$. The 13-year-olds did not differ from adults, $t(19) = 0.82$, $p = .40$, $d = 0.04$. In summary, the magnitude of the fission illusion was statistically adult-like by 11 years of age, whereas the magnitude of the fusion illusion may still not be fully adult-like until beyond age 11.

[3] Significance confirmed by independent bootstrap analysis ($p = .03$).

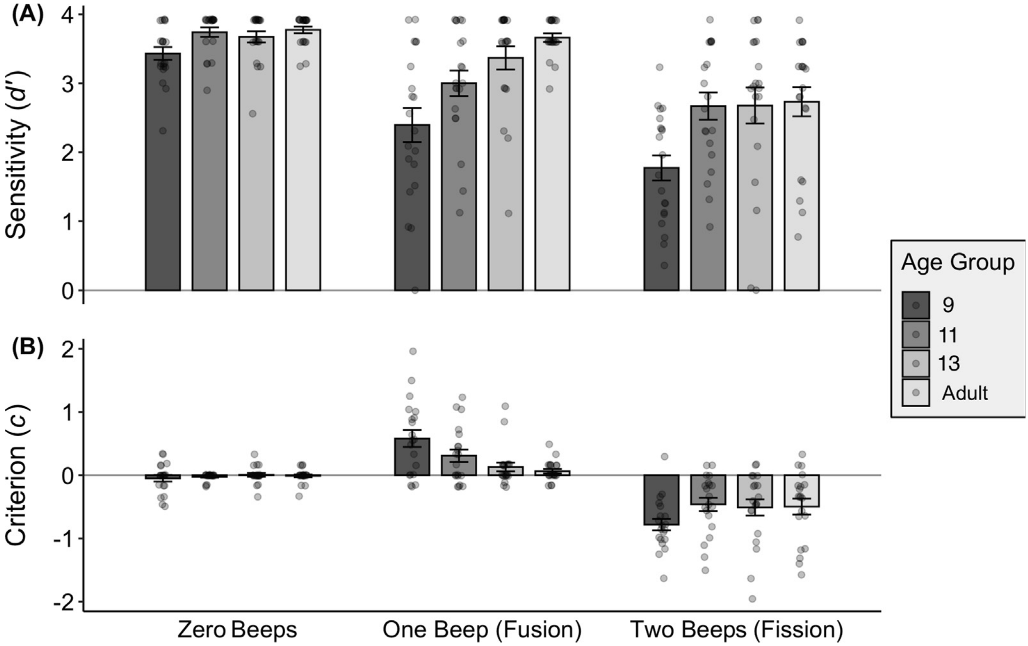

Fig. 4. Signal detection: Discriminability (d') and criterion (c) associated with the sound-induced tap illusion. (A) Mean d' scores for the four age groups tested. The d' represents the ability to distinguish two taps (target) from one tap (noise) when paired with either zero beeps (unimodal), one beep, or two beeps. (B) Mean c scores for the four age groups tested. A shift toward a positive criterion indicates a bias to report one tap, whereas a shift toward a negative criterion indicates a bias to report two taps. Individual data points represent the mean d' and c of each participant in Panels A and B, respectively. Fission is represented in the two-beep condition (right), whereas fusion is represented in the one-beep condition (middle). Error bars are ±1 standard error of the mean.

Signal detection analysis

Discriminability (d′)

The d' values were greater than zero for all beep and age conditions, all $ts(19) > 37.18$, $ps < .001$, $ds > 2.18$ (see Fig. 4A), confirming that all age groups were able to discriminate between one and two taps.

The effect of age was significant for all three one-way ANOVAs [zero beeps: $F(3,76) = 4.31$, $p = .007$, $\eta^2_p = .15$; one beep: $F(3,76) = 9.37$, $p < .001$, $\eta^2_p = .27$; two beeps: $F(3,76) = 4.58$, $p = .005$, $\eta^2_p = .15$].[4] The Dunnett's tests showed that 9-year-olds had a lower d' than adults in all beep conditions [zero beeps: $t(19) = -3.25$, $p = .002$, $d = 0.71$; one beep: $t(19) = -5.02$, $p < .001$, $d = 1.17$; two beeps: $t(19) = -3.15$, $p = .003$, $d = 0.74$). The 11-year-olds had a lower d' than the adults in the one-beep condition, $t(19) = -5.02$, $p = .01$, $d = 0.85$; however, they did not differ significantly from adults in the zero-beep and two-beep conditions, both $ts(19) < 0.31$, $ps > .63$, $ds < 0.09$. The 13-year-olds were adult-like for all three beep conditions, all $ts(19) < 1.16$, $ps > .26$, $ds < 0.35$).

Criterion (c)

For the zero-beep condition, none of the age groups differed from zero, all $ts(19) < 0.41$, $ps > .38$, $ds < 0.20$ (two-tailed), suggesting that they had no bias to report one or two taps in the absence of

[4] Although these one-way ANOVAs for each level of beep were planned a priori (see "Analysis" section for rationale), we conducted a two-way ANOVA with the factor of beep (zero, one, or two beeps) and age (9-year-olds, 11-year-olds, 13-year-olds, or adults), which confirmed a significant two-way interaction ($p = .04$).

sound. In the one-beep condition, all age groups had criterion scores greater than zero, all *t*s(19) > 1.80, *p*s < .04, *d*s > 0.40, indicating a bias to report one tap, consistent with the characteristic of the fusion illusion. In the two-beep condition, all age groups demonstrated criteria below zero, all *t*s(19) > −3.92, *p*s < .001, *d*s > 0.88, representing an overall bias to report two taps, consistent with the characteristic of the fission illusion.

For each level of beep, the effect of age was significant in the one-beep condition, $F(3,76) = 6.27$, $p < .001$, $\eta_p^2 = .20$, but not in the zero-beep condition, $F(3,76) = 0.49$, $p = .69$, $\eta_p^2 = .02$, or the two-beep condition, $F(3,76) = 1.67$, $p = .18$, $\eta_p^2 = .06$.[5] The Dunnett's test revealed that in the one-beep condition, 9-year-olds had a significantly larger bias to report one tap compared with adults, $t(19) = 3.96$, $p < .001$, $d = 0.78$, whereas 11-year-olds had a bias that was only marginally larger than that of adults, $t(19) = 1.88$, $p = .08$, $d = 0.58$. The 13-year-olds did not differ from the adults, $t(19) = 0.51$, $p = .54$, $d = 0.18$. In summary, the 9-year-olds and some 11-year-olds were more biased than the adults in the one-beep condition representative of the fusion illusion.

Discussion

We tested three groups of children (9-, 11-, and 13-year-olds) and one group of adults on the sound-induced tap illusion and tap-induced sound illusion. For the sound-induced tap illusion, we observed fission in all four groups and fusion in only the three groups of children. The magnitude of both illusions was greatest in 9-year-olds when compared with adults. The fission illusion is reduced to an adult-like magnitude by 11 years of age, whereas the fusion illusion might not be fully adult-like until 13 years of age. The signal detection analysis revealed that 9-year-olds had poorer discriminability than adults for both the fission and fusion illusions and had a significant bias to report one tap in the fusion illusion. The 11-year-olds also had poorer discriminability than adults and a marginal bias to report one tap in the fusion illusion. Thus, the fission and fusion illusions show different developmental trajectories; fission is adult-like by 11 years of age, which is primarily explained by children's improved discriminability, whereas fusion requires an additional two years of development, which can be attributed to both improved discriminability and a less biased criterion.

A transition from immature during late childhood (<10 years of age) to mature during early adolescence (∼11–13 years of age) for the sound-induced tap illusions mirrors the maturation of audiotactile simultaneity perception (Stanley et al., 2019). Both studies used identical stimuli (with minor differences in associated parameters, such as temporal intervals between stimuli) and similar experimental context but differed in the type of temporal task (event counting and simultaneity perception), thereby providing convergent evidence that 9 to 13 years of age appears to be a critical transition period of maturation in audiotactile perception. This age range is also similar to other tasks involving visual flash illusions in which children begin to show adult-like multisensory integration: approximately 8 to 10 years for audiovisual (Adams, 2016; Nava & Pavani, 2013) and approximately 10 to 12 years for visuotactile (O'Dowd et al., 2021). For audiohaptic integration, Scheller et al. (2021) reported a later maturation age (adult-like by ∼15 years of age). Whereas both the current study and their study supported a late maturation, the later age observed in their study could be attributed to different tasks and associated information processing; Scheller et al.'s task required estimation of object size using active touch (i.e., haptic), whereas the task in the current study required numerosity judgments using passive touch (i.e., tactile) (see Heller, 1984, and Simões-Franklin et al., 2011). In addition, it has been proposed that spatial abilities mature after temporal abilities (see Scheller et al., 2021). Finally, mature integration in Scheller et al.'s (2021) study was determined by optimal cue integration; although the fission and fusion illusions can be explained by optimal integration (Andersen et al., 2004; Bresciani & Ernst, 2007; Shams et al., 2005; Wozny et al., 2008), we did not measure optimality, which may mature later than the benchmark for adult-like perception used in the current study. Regardless, the development of cross-modal abilities involving active touch (e.g.,

[5] Although these one-way ANOVAs for each level of beep were planned a priori (see "Analysis" section for rationale), we conducted a two-way ANOVA with the factor of beep (zero, one, or two beeps) and age (9-year-olds, 11-year-olds, 13-year-olds, or adults), which confirmed a significant two-way interaction ($p < .001$).

size estimation) appears to stretch into late adolescence, whereas we see adult-like audiotactile abilities in the temporal domain slightly earlier by 11 to 13 years of age.

To account for the developmental trends observed, we can consider several theories within multisensory perception. During early development, children demonstrate sensory dominance (e.g., Gori et al., 2008, 2012; Nava & Pavani, 2013); sensory signals are not integrated, and the modality with greater precision drives perception. In the current study, audition appears to be the dominant sense because we observed only a weak tap-induced sound fission illusion and no tap-induced sound fusion illusion (see supplementary material for discussion), implying that the tactile signal was less salient (i.e., less reliable) than the auditory signal. Sensory dominance gives way to multisensory integration as children age; the transition, based on prior research with audiovisual and visuotactile tasks, appears to reach completion by around 10 years of age (Adams, 2016; Gori et al., 2008, 2012, 2021; Nava & Pavani, 2013; see Burr & Gori, 2012, for a review). This could account for the larger illusions observed in the 9- and 11-year-olds in the current study if we assume that this transition occurs later for audiotactile pairings (plausibly after age 11), which is consistent with protracted development when touch is involved (see Introduction).

Alternatively, 9- and 11-year-olds may have already transitioned to multisensory integration, in which case perception would be driven by remaining immaturities in a multisensory integration process such as optimal cue combination (see Alais & Burr, 2004; Ernst & Banks, 2002; Ernst & Bülthoff, 2004). To date, several developmental studies have charted the development of optimal integration, which appears to emerge between late childhood and late adolescence depending on the task (Adams, 2016; Gori et al., 2008, 2012, 2021; Nardini et al., 2008; Petrini et al., 2014; Scheller et al., 2021). Optimal integration is often modeled using maximum likelihood estimation (MLE) in which the final integrative percept is determined by the relative weights of the unimodal sensory signals in terms of their reliabilities. Recall that the 9-year-olds had significantly worse unimodal tactile perception than adults (see Fig. 4A); when combined with the finding of 9-year-olds' adult-like unimodal auditory accuracy (see Fig. S3 in supplementary material), we can assume that audition had a greater relative reliability within this age group given the stimulus parameters used. This greater reliability of audition would cause an MLE-based integration mechanism to produce the larger magnitudes of fission and fusion observed in the 9-year-olds. However, the 11-year-olds had an immature fusion illusion even though they demonstrated adult-like unimodal tactile accuracy, which thus requires additional theoretical considerations. In addition, the standard MLE model assumes weighted integration occurs on every trial and fails to consider circumstances in which signals should be segregated (Shams et al., 2005; Wozny et al., 2008). Specifically, sometimes the illusions were not perceived (i.e., accuracy in the incongruent trials was greater than 0), which means that the auditory and tactile signals were likely processed independently.

The Bayesian causal inference framework incorporates a weighted MLE process and adds a weighted prior for one versus two sources based on experience, expectancy, task context, and stimulus parameters (Körding et al., 2007; Wozny et al., 2010). The addition of the weighted prior allows for sensory segregation (see Shams & Beierholm, 2010, Fig. 2), which is important to consider here because the magnitudes of fission and fusion are derived from the proportion of trials in which integration did or did not occur. This prior, at least for adults, is assumed to weight the one- and two-source hypotheses appropriately given the context. The greater illusion in 9-year-olds therefore could result from an immature prior that favors a single source (i.e., integration). At this age, they are just beginning to experience the perceptual advantage produced by an MLE-based integration process (i.e., multisensory gains: superior precision for integrated percepts than for either of the unisensory percepts alone; see Ernst & Bülthoff, 2004). However, children at this age and younger may lack the experience with perceptual errors that result from spurious integrations which ultimately balance the prior between one and two sources. Gaining this experience may also contribute to the development of an adult-like ability to rapidly recalibrate (e.g., Han et al., 2022; Rohlf et al., 2020). Nevertheless, given that 11-year-olds show only immature fusion but adult-like fission and show ceiling unimodal accuracy, this account alone—a biased prior for one source—cannot account for all these data. Clearly, these ideas are speculative because studies addressing the nature of priors remain in their infancy (Shams & Beierholm, 2022), and we are not aware of any studies exploring changes in priors across development. To disentangle these multiple accounts for our data will require future research specifically designed to independently estimate the priors and the MLE function, and the possibility of sensory dominance.

Finally, we must also entertain the possibility that the different developmental trends for fission and fusion require independent explanations. Although the fission and fusion illusions are generally perceptual in nature, there are suggestions in the literature that different mechanisms may underlie the two illusions (e.g., Bolognini et al., 2011; Bolognini et al., 2016; Chen et al., 2017; Mishra et al., 2007; Mishra et al., 2008; see Hirst et al., 2020, for a review of the audiovisual data). Specifically, there are hints that the fusion illusion may be more affected by decisional factors than the fission illusion (see Chen et al., 2017, for a discussion). Qualitative examination of the magnitude of illusions (Fig. 3) suggests that fission develops in a step-like function after 9 years of age, whereas fusion has a more gradual refinement across development. Decisional processes, especially those involved with inhibition of irrelevant signals, appear to have a protracted development (Hooper et al., 2004), and could result in the later maturation of the fusion illusion.

Conclusions

Audiotactile integration measured with the current task was completely adult-like by 13 years of age. The fission and fusion illusions, used to measure integration, appear to follow different developmental trends. Based on the magnitude of illusions and the signal detection analysis, fission reaches maturity by 11 years of age, whereas fusion is not fully mature until 13 years of age. Theoretical accounts of these data considered sensory dominance, optimal integration mechanisms (i.e., MLE), and the prior for one or two sources associated with causal inference. Further research is needed to specify the relative contributions of these accounts.

CRediT authorship contribution statement

Brendan M. Stanley: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing – original draft, Data curation, Visualization, Project administration. **Yi-Chuan Chen:** Conceptualization, Methodology, Software, Writing – review & editing. **Daphne Maurer:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Funding acquisition. **Terri L. Lewis:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Funding acquisition. **David I. Shore:** Conceptualization, Methodology, Software, Formal analysis, Resources, Writing – original draft, Visualization, Supervision, Funding acquisition.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jecp.2023.105629.

References

Adams, W. J. (2016). The development of audio-visual integration for temporal judgements. *PLoS Computational Biology, 12*(4), 1–17. https://doi.org/10.1371/journal.pcbi.1004865.

Alais, D., & Burr, D. (2004). The ventriloquist effect results from near-optimal bimodal integration. *Current Biology, 14*(3), 257–262. https://doi.org/10.1016/j.cub.2004.01.029.

Andersen, T. S., Tiippana, K., & Sams, M. (2004). Factors influencing audiovisual fission and fusion illusions. *Cognitive Brain Research, 21*(3), 301–308. https://doi.org/10.1016/j.cogbrainres.2004.06.004.
Begum Ali, J., Spence, C., & Bremner, A. J. (2015). Human infants' ability to perceive touch in external space develops postnatally. *Current Biology, 25*(20), R978–R979. https://doi.org/10.1016/j.cub.2015.08.055.
Bolognini, N., Convento, S., Casati, C., Mancini, F., Brighina, F., & Vallar, G. (2016). Multisensory integration in hemianopia and unilateral spatial neglect: Evidence from the sound induced flash illusion. *Neuropsychologia, 87*, 134–143. https://doi.org/10.1016/j.neuropsychologia.2016.05.015.
Bolognini, N., Rossetti, A., Casati, C., Mancini, F., & Vallar, G. (2011). Neuromodulation of multisensory perception: A tDCS study of the sound-induced flash illusion. *Neuropsychologia, 49*(2), 231–237. https://doi.org/10.1016/j.neuropsychologia.2010.11.015.
Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision, 10*, 433–436. https://doi.org/10.1163/156856897X00357.
Bremner, A. J., & Spence, C. (2017). The development of tactile perception. *Advances in Child Development and Behavior, 52*, 227–268. https://doi.org/10.1016/bs.acdb.2016.12.002.
Bresciani, J.-P., Dammeier, F., & Ernst, M. O. (2008). Tri-modal integration of visual, tactile and auditory signals for the perception of sequences of events. *Brain Research Bulletin, 75*, 753–760. https://doi.org/10.1016/j.brainresbull.2008.01.009.
Bresciani, J. P., & Ernst, M. O. (2007). Signal reliability modulates auditory–tactile integration for event counting. *NeuroReport, 18*(11), 1157–1161. https://doi.org/10.1097/WNR.0b013e3281ace0ca.
Bresciani, J. P., Ernst, M. O., Drewing, K., Bouyer, G., Maury, V., & Kheddar, A. (2005). Feeling what you hear: Auditory signals can modulate tactile tap perception. *Experimental Brain Research, 162*(2), 172–180. https://doi.org/10.1007/s00221-004-2128-2.
Bremner, A. J., Holmes, N. P., & Spence, C. (2012). The development of multisensory representations of the body and of the space around the body. In A. J. Bremner, D. J. Lewkowicz, & C. Spence (Eds.), Multisensory development (pp. 113–136). Oxford University Press. https://doi.org/10.1093/acprof:oso/9780199586059.003.0005 (https://psycnet.apa.org/doi/10.1093/acprof:oso/9780199586059.003.0005).
Burr, D., & Gori, M. (2012). Multisensory integration develops late in humans. In M. M. Murray & M. T. Wallace (Eds.), *The neural bases of multisensory processes* (pp. 345–362). CRC Press/Taylor & Francis. https://doi.org/10.1201/b11092-23.
Chen, Y. C., Lewis, T. L., Shore, D. I., Spence, C., & Maurer, D. (2018). Developmental changes in the perception of visuotactile simultaneity. *Journal of Experimental Child Psychology, 173*, 304–317. https://doi.org/10.1016/j.jecp.2018.04.014.
Chen, Y. C., Maurer, D., Lewis, T. L., Spence, C., & Shore, D. I. (2017). Central–peripheral differences in audiovisual and visuotactile event perception. *Attention, Perception, & Psychophysics, 79*(8), 2552–2563. https://doi.org/10.3758/s13414-017-1396-4.
Chen, Y. C., Shore, D. I., Lewis, T. L., & Maurer, D. (2016). The development of the perception of audiovisual simultaneity. *Journal of Experimental Child Psychology, 146*, 17–33. https://doi.org/10.1016/j.jecp.2016.01.010.
Ernst, M. O. (2008). Multisensory integration: A late bloomer. *Current Biology, 18*(12), 519–521. https://doi.org/10.1016/j.cub.2008.05.003.
Ernst, M. O., & Banks, M. S. (2002). Humans integrate visual and haptic information in a statistically optimal fashion. *Nature, 415*(6870), 429–433. https://doi.org/10.1038/415429a.
Ernst, M. O., & Bülthoff, H. H. (2004). Merging the senses into a robust percept. *Trends in Cognitive Sciences, 8*(4), 162–169. https://doi.org/10.1016/j.tics.2004.02.002.
Gori, M., Campus, C., & Cappagli, G. (2021). Late development of audio-visual integration in the vertical plane. *Current Research in Behavioral Sciences, 2*. https://doi.org/10.1016/j.crbeha.2021.100043. Article 100043.
Gori, M., Del Viva, M., Sandini, G., & Burr, D. C. (2008). Young children do not integrate visual and haptic form information. *Current Biology, 18*(9), 694–698. https://doi.org/10.1016/j.cub.2008.04.036.
Gori, M., Sandini, G., & Burr, D. (2012). Development of visuo-auditory integration in space and time. *Frontiers in Integrative Neuroscience, 6*. https://doi.org/10.3389/fnint.2012.00077. Article 77.
Han, S., Chen, Y.-C., Maurer, D., Shore, D. I., Lewis, T. L., Stanley, B. M., & Alais, D. (2022). The development of audio-visual temporal precision precedes its rapid recalibration. *Scientific Reports, 12*(1). https://doi.org/10.1038/s41598-022-25392-y. Article 21591.
Held, R., Ostrovsky, Y., Degelder, B., Gandhi, T., Ganesh, S., Mathur, U., & Sinha, P. (2011). The newly sighted fail to match seen with felt. *Nature Neuroscience, 14*(5), 551–553. https://doi.org/10.1038/nn.2795.
Heller, M. A. (1984). Active and passive touch: The influence of exploration time on form recognition. *Journal of General Psychology, 110*, 243–249. https://doi.org/10.1080/00221309.1984.9709968.
Hirst, R. J., McGovern, D. P., Setti, A., Shams, L., & Newell, F. N. (2020). What you see is what you hear: Twenty years of research using the sound-induced flash illusion. *Neuroscience and Biobehavioral Reviews, 118*, 759–774. https://doi.org/10.1016/j.neubiorev.2020.09.006.
Hooker, D. (1958). *Evidence of prenatal function of the central nervous system in man* (James Arthur Lecture on the Evolution of the Human Brain, No. 26, 1957). American Museum of Natural History.
Hooper, C. J., Luciana, M., Conklin, H. M., & Yarger, R. S. (2004). Adolescents' performance on the Iowa Gambling Task: Implications for the development of decision making and ventromedial prefrontal cortex. *Developmental Psychology, 40*(6), 1148–1158. https://doi.org/10.1037/0012-1649.40.6.1148.
Hötting, K., & Röder, B. (2004). Hearing cheats touch, but less in congenitally blind than in sighted individuals. *Psychological Science, 15*(1), 60–64. https://doi.org/10.1111/j.0963-7214.2004.01501010.x.
Innes-Brown, H., Barutchu, A., Shivdasani, M. N., Crewther, D. P., Grayden, D. B., & Paolini, A. (2011). Susceptibility to the flash-beep illusion is increased in children compared to adults. *Developmental Science, 14*(5), 1089–1099. https://doi.org/10.1111/j.1467-7687.2011.01059.x.
Kisilevsky, B. S., & Muir, D. W. (1991). Human fetal and subsequent newborn responses to sound and vibration. *Infant Behavior and Development, 14*(1), 1–26. https://doi.org/10.1016/0163-6383(91)90051-S.
Kleiner, M., Brainard, D., Pelli, D., Ingling, A., Murray, R., Broussard, C., & Cornelissen, F. (2007). *What's new in Psychtoolbox-3? A free cross-platform toolkit for Psychophysics with Matlab & GNU/Octave.* http://www.psychtoolbox.org.
Körding, K. P., Beierholm, U., Ma, W. J., Quartz, S., Tenenbaum, J. B., & Shams, L. (2007). Causal inference in multisensory perception. *PLoS One, 2*(9). https://doi.org/10.1371/journal.pone.0000943. Article e943.

Machulla, T.-K., Di Luca, M., & Ernst, M. O. (2016). The consistency of crossmodal synchrony perception across the visual, auditory, and tactile senses. *Journal of Experimental Psychology: Human Perception and Performance, 42*(7), 1026–1038. https://doi.org/10.1037/xhp0000191.

Maurer, D., Stager, C. L., & Mondloch, C. J. (1999). Cross-modal transfer of shape is difficult to demonstrate in one-month-olds. *Child Development, 70*(5), 1047–1057. https://doi.org/10.1111/1467-8624.00077.

McCormick, D., & Mamassian, P. (2008). What does the illusory-flash look like? *Vision Research, 48*(1), 63–69. https://doi.org/10.1016/j.visres.2007.10.010.

Mishra, J., Martinez, A., & Hillyard, S. A. (2008). Cortical processes underlying sound-induced flash fusion. *Brain Research, 1242*, 102–115. https://doi.org/10.1016/j.brainres.2008.05.023.

Mishra, J., Martinez, A., Sejnowski, T. J., & Hillyard, S. A. (2007). Early cross-modal interactions in auditory and visual cortex underlie a sound-induced visual illusion. *Journal of Neuroscience, 27*(15), 4120–4131. https://doi.org/10.1523/JNEUROSCI.4912-06.2007.

Nardini, M., Jones, P., Bedford, R., & Braddick, O. (2008). Development of cue integration in human navigation. *Current Biology, 18*(9), 689–693. https://doi.org/10.1016/j.cub.2008.04.021.

Nava, E., & Pavani, F. (2013). Changes in sensory dominance during childhood: Converging evidence from the Colavita effect and the sound-induced flash illusion. *Child Development, 84*(2), 604–616. https://doi.org/10.1111/j.1467-8624.2012.01856.x.

Occelli, V., Spence, C., & Zampini, M. (2011). Audiotactile interactions in temporal perception. *Psychonomic Bulletin & Review, 18*(3), 429–454. https://doi.org/10.3758/s13423-011-0070-4.

O'Dowd, A., Cooney, S. M., Sorgini, F., O'Rourke, E., Reilly, R. B., Newell, F. N., & Hirst, R. J. (2021). The development of visuotactile congruency effects for sequences of events. *Journal of Experimental Child Psychology, 207*. https://doi.org/10.1016/j.jecp.2021.105094. Article 105094.

Pelli, D. G. (1997). The Videotoolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision, 10*(4), 437–442. https://doi.org/10.1163/156856897x00366.

Petrini, K., Remark, A., Smith, L., & Nardini, M. (2014). When vision is not an option: Children's integration of auditory and haptic information is suboptimal. *Developmental Science, 17*(3), 376–387. https://doi.org/10.1111/desc.12127.

Rohlf, S., Li, L., Bruns, P., & Röder, B. (2020). Multisensory integration develops prior to crossmodal recalibration. *Current Biology, 30*(9), 1726–1732. https://doi.org/10.1016/j.cub.2020.02.048.

Scheller, M., Proulx, M. J., de Haan, M., Dahlmann-Noor, A., & Petrini, K. (2021). Late- but not early-onset blindness impairs the development of audio-haptic multisensory integration. *Developmental Science, 24*(1). https://doi.org/10.1111/desc.13001. Article e13001.

Shams, L., & Beierholm, U. (2022). Bayesian causal inference: A unifying neuroscience theory. *Neuroscience & Biobehavioral Reviews, 137*. https://doi.org/10.1016/j.neubiorev.2022.104619. Article 104619.

Shams, L., & Beierholm, U. R. (2010). Causal inference in perception. *Trends in Cognitive Sciences, 14*(9), 425–432. https://doi.org/10.1016/j.tics.2010.07.001.

Shams, L., Kamitani, Y., & Shimojo, S. (2000). What you see is what you hear. *Nature, 408*(6814), Article 788. https://doi.org/10.1038/35048669.

Shams, L., Kamitani, Y., & Shimojo, S. (2002). Visual illusion induced by sound. *Cognitive Brain Research, 14*(1), 147–152. https://doi.org/10.1016/S0926-6410(02)00069-1.

Shams, L., Ma, W. J., & Beierholm, U. (2005). Sound-induced flash illusion as an optimal percept. *NeuroReport, 16*(17), 1923–1927. https://doi.org/10.1097/01.wnr.0000187634.68504.bb.

Simões-Franklin, C., Whitaker, T. A., & Newell, F. N. (2011). Active and passive touch differentially activate somatosensory cortex in texture perception. *Human Brain Mapping, 32*(7), 1067–1080. https://doi.org/10.1002/hbm.21091.

Stanley, B. M., Chen, Y. C., Lewis, T. L., Maurer, D., & Shore, D. I. (2019). Developmental changes in the perception of audiotactile simultaneity. *Journal of Experimental Child Psychology, 183*, 208–221. https://doi.org/10.1016/j.jecp.2019.02.006.

Stone, J. V., Hunkin, N. M., Porrill, J., Wood, R., Keeler, V., Beanland, M., Port, M., & Porter, N. R. (2001). When is now? Perception of simultaneity. *Proceedings of the Royal Society: Biological Sciences, 268*(1462), 31–38. https://doi.org/10.1098/rspb.2000.1326.

Welch, R. B., & Warren, D. H. (1980). Immediate perceptual response to intersensory discrepancy. *Psychological Bulletin, 88*(3), 638–667. https://doi.org/10.1037/0033-2909.88.3.638.

Wozny, D. R., Beierholm, U. R., & Shams, L. (2008). Human trimodal perception follows optimal statistical inference. *Journal of Vision, 8*(3). https://doi.org/10.1167/8.3.24. Article 24.

Wozny, D. R., Beierholm, U. R., & Shams, L. (2010). Probability matching as a computational strategy used in perception. *PLoS Computational Biology, 6*(8). https://doi.org/10.1371/journal.pcbi.1000871. Article e1000871.

Zampini, M., Guest, S., Shore, D. I., & Spence, C. (2005). Audio-visual simultaneity judgments. *Perception & Psychophysics, 67*(3), 531–544. https://doi.org/10.3758/BF03193329.