Journal of Experimental Child Psychology 183 (2019) 208–221

Contents lists available at ScienceDirect

Journal of Experimental Child Psychology

journal homepage: www.elsevier.com/locate/jecp

Developmental changes in the perception of audiotactile simultaneity

Brendan M. Stanley [a], Yi-Chuan Chen [b], Terri L. Lewis [a], Daphne Maurer [a], David I. Shore [a,*]

[a] Department of Psychology, Neuroscience & Behaviour, McMaster University, Hamilton, Ontario L8S 4K1, Canada
[b] Department of Medicine, Mackay Medical College, New Taipei City 252, Taiwan

ARTICLE INFO

Article history:

Keywords:
Multisensory
Crossmodal
Development
Audition
Touch
Children
Simultaneity judgments
Point of subjective simultaneity

ABSTRACT

We charted the developmental trajectory of the perception of audiotactile simultaneity by testing three groups of children (aged 7, 9, and 11 years) and one group of adults. A white noise burst and a tap to the index finger were presented at 1 of 13 stimulus onset asynchronies (SOAs), and the participants were asked to report whether the two stimuli were simultaneous. Compared with adults, 7-year-olds made significantly more simultaneous responses at 9 of the 13 SOAs, whereas 9-year-olds differed from adults at only 2 SOAs. The precision of simultaneity perception was lower, and response errors were higher, in younger children than in adults. The 11-year-olds were adult-like on all measures, thereby demonstrating that judgments about simultaneity for audiotactile stimuli are mature by 11 years. This developmental pattern is similar to that for simultaneity perception for visuotactile stimuli but later than that for audiovisual stimuli. The longer developmental trajectories of the perception of simultaneity between touch and vision and between touch and audition may arise from the need to coordinate and recalibrate between different reference frames and different neural transmission times in each sensory system during body growth; in addition, the ubiquity of audiovisual experience in everyday life may accelerate the development of that modality pairing.

© 2019 Published by Elsevier Inc.

* Corresponding author.
E-mail address: dshore@mcmaster.ca (D.I. Shore).

https://doi.org/10.1016/j.jecp.2019.02.006
0022-0965/© 2019 Published by Elsevier Inc.

Introduction

Temporal synchrony provides one of the fundamental cues governing multisensory perception (Stein & Meredith, 1993; Welch & Warren, 1980; see Vroomen & Keetels, 2010, for a review). When two or more stimuli are presented to different modalities in temporal proximity, they tend to be perceived as simultaneous, as if originating from a single event. Spatial proximity provides another cue. At birth, newborns are already sensitive to these parameters for auditory and visual signals (Lewkowicz, Leo, & Simion, 2010; Morrongiello, Fenwick, & Chance, 1998) and for visual and tactile signals (Filippetti, Johnson, Lloyd-Fox, Dragovic, & Farroni, 2013). For audiotactile pairings, even the fetus is sensitive to temporal correspondence (Kisilvesky & Muir, 1991). Even though these early multisensory abilities establish a foundation, recent studies have demonstrated that the developmental trajectory for the perception of multisensory simultaneity is protracted (e.g., Chen, Lewis, Shore, Spence, & Maurer, 2018; Chen, Shore, Lewis, & Maurer, 2016; Lewkowicz & Flom, 2014; Röder, Pagel, & Heed, 2013).

Measuring simultaneity perception in older children and adults is typically accomplished with a simultaneity judgment task (e.g., Chen et al., 2016, 2018; Hillock, Powers, & Wallace, 2011; Hillock-Dunn & Wallace, 2012; Stevenson, Baum, Krueger, Newhouse, & Wallace, 2018). In this paradigm, two stimuli, each delivered to a different sensory modality, are presented either simultaneously or separated by predetermined stimulus onset asynchronies (SOAs). Participants report whether the stimuli were perceived as synchronous. Based on the percentage of simultaneous responses as a function of the SOAs, two parameters about the window of multisensory simultaneity perception can be estimated: (a) the point of subjective simultaneity (PSS), which reflects the estimated SOA that yields the highest probability that the stimuli were perceived as simultaneous, and (b) the width of the temporal window, which reflects the range of SOAs at which participants reliably perceived simultaneity above a certain criterion. These two measures of performance are independent of each other given that they tap theoretically different mechanisms; the PSS reflects the relative processing times of the signals in each modality, whereas the width of the window is a proxy for the variability of the arrival times for those signals (see García-Pérez & Alcalá-Quintana, 2012a, 2012b). How these two measures change across development can be used to assess their independence. Specifically, Chen et al. (2016) demonstrated that, for audiovisual pairings, 5- and 7-year-olds have a significantly wider temporal simultaneity window, which reaches adult-like width by 9 years of age.[1] The PSS of the audiovisual simultaneity window was reported on the vision-leading side at 5 years of age (the youngest age group tested), suggesting that, from at least 5 years onward, the visual signal needs to be presented earlier in order for it to be perceived as simultaneous with the auditory signal. This is most likely caused by slower sensory transduction for vision than for audition (Chen et al., 2016). For visuotactile pairings

[1] It is worth noting that other studies have demonstrated a later age of maturation for the perception of audiovisual simultaneity (Hillock et al., 2011; Hillock-Dunn & Wallace, 2012; Stevenson et al., 2018). However, methodological differences that likely account for this discrepancy include the following. First, the three studies reporting a later maturation age tested wider age ranges within groups (±30 months in Hillock-Dunn and Wallace (2012), ±42 months in Stevenson et al. (2018), and unavailable in Hillock et al. (2011) vs. ±3 months in Chen et al. (2016, 2018) and the current study). Second, Hillock et al. (2011), Hillock-Dunn and Wallace (2012), and Stevenson et al. (2018) used general mathematical fitting methods to estimate the width of the window, whereas Chen et al. (2016, 2018) and the current study used a model designed specifically for simultaneity judgment tasks developed by García-Pérez and Alcalá-Quintana (2012a, 2012b). This model is based on assumptions of human sensory processing and accounts for response errors and lapses in attention. Third, Hillock et al. (2011), Hillock-Dunn and Wallace (2012), and Stevenson et al. (2018) did not report whether or how they rejected outliers, which can be critical to ensure that the reported results represent only children who concentrated on the task. Any of these factors may contribute to poorer measures and estimates of changes across development, making direct comparisons across the literature impossible (see Chen et al. (2016, 2018) for discussions of these factors). Finally, different criteria were used to determine the width of the audiovisual simultaneity window; 75% simultaneity responses were used in Hillock et al.'s (2011), Hillock-Dunn and Wallace's (2012), and Stevenson et al.'s (2018) studies, whereas 50% simultaneity responses were used in Chen et al. (2016, 2018) and the current study. On the same simultaneity judgment curve, different criteria can yield different measures of the width of the temporal window (see Kaganovich, 2016). In the current study, we used the same methodological details and fitting function as the Chen et al. (2016, 2018) studies, making these the best points of comparison across modality pairings.

(Chen et al., 2018), children did not reach an adult-like width of the window until 11 years of age, but the PSS was already located on the tactile-leading side by 7 years (the youngest age group tested). Given the rapid transduction of vibrotactile stimulation, this PSS shift toward the tactile-leading side probably results from the neural transmission time taking longer from the finger to the brain than the time it takes to process the visual signal.

The current study aimed to chart the developmental trajectory of audiotactile pairings in order to complete the comparison across all combinations of the three physical senses (i.e., those senses with a spatial representation such as vision, audition, and touch). Importantly, similar stimuli were used across the measurement of the three pairings (audiovisual, visuotactile, and audiotactile). This comparison will help to resolve the question about whether a common mechanism or separate mechanisms underlie simultaneity perception for different modality pairings (e.g., see Vroomen & Keetels, 2010). If the perception of audiotactile simultaneity develops similarly to audiovisual simultaneity, we could infer that audition is the determining factor driving its development, perhaps because of its high temporal resolution and/or processing speed. Alternatively, if the developmental trajectory is found to be similar to visuotactile simultaneity perception, we could infer that the determining factor would be touch, perhaps because it has the slowest processing speed and/or a later unimodal developmental trajectory (see Section Discussion). Finally, if the age of maturation is different from both audiovisual and visuotactile pairings, we would conclude that each modality pairing has its own temporal processing mechanism, and thus, they mature independently of one another.

Audiotactile interactions provide an interesting pairing because of the unique relation between these modalities (see Occelli, Spence, & Zampini, 2011). Unlike vision, both modalities are stimulated by mechanical displacement of a membrane by air/physical pressure (Soto-Faraco & Deco, 2009). Compared with vision, both modalities also have shorter transduction latencies (Barnett-Cowan & Harris, 2009). In adults, the temporal resolution for the pairing of sound and touch is higher than that for audiovisual or visuotactile pairings (Fujisaki & Nishida, 2009). Among the spatial senses, sound and touch experienced in close temporal proximity have a high likelihood of being causally related to self-generated actions (e.g., texture discrimination: Guest, Catmur, Lloyd, & Spence, 2002; Jousmäki & Hari, 1998). Taken together, these studies highlight the special nature of audiotactile interactions compared with those that involve vision.

The current study investigated the developmental trajectory for the perception of audiotactile simultaneity by comparing three groups of children (aged 7, 9, and 11 years) to adults. These age groups were chosen because we expected that audiotactile simultaneity perception matures during late childhood based on previous studies of the other modality pairings (Chen et al., 2016, 2018). The simultaneity judgment task required participants to judge whether a beep and tap were presented simultaneously. The stimuli (beeps and taps) were presented either simultaneously or at one of 12 SOAs, ranging from sound leading by 1200 ms to sound lagging by 1200 ms. The dependent variable of interest was the proportion of simultaneous responses at each SOA. These data were subjected to the bootstrap procedure developed by García-Pérez and Alcalá-Quintana (2012a, 2012b) to extract the parameters of PSS and the width of the simultaneity window while estimating parameters associated with peripheral sensory processing and response errors separately (see below). The experimental design, stimuli, and data analysis were similar to those in previous studies on the development of audiovisual and visuotactile simultaneity (Chen et al., 2016, 2018) except for the location of the auditory stimulus (headphones in the current study vs. free field in Chen et al., 2016) and the duration of the stimuli (10 ms in the current study vs. 17 ms in Chen et al., 2016, 2018). Hence, the developmental trajectory of audiovisual, visuotactile, and audiotactile simultaneity perception obtained in these three studies can be compared.

Method

Participants

Four age groups, each with 20 participants, were included in the analyses: 7-year-olds (mean age = 7.0 years, range = 6.8–7.3; 7 boys), 9-year-olds (mean age = 9.1 years, range = 8.9–9.3; 10 boys), 11-year-olds (mean age = 11.1 years, range = 10.8–11.3; 10 boys), and adults (mean age = 22.0 years, range = 17.9–37.1; 10 men). All participants were right-handed and had normal auditory and tactile acuity by self-report, and all passed the Randot test of stereoacuity (minimum of 40 s of arc achieved). The visual test was included to ensure that the participants were comparable to those tested in the previous studies of the perception of audiovisual and visuotactile simultaneity, all of whom had normal binocular vision, the visual function that is most susceptible to abnormal early visual experience. An additional 11 children were tested but excluded because of technical problems (three 11-year-olds) or because they did not pass the stereoacuity test (one 7-year-old and one 9-year-old), did not complete the experiment (two 7-year-olds), or did not pass criterion for the practice block (see below; two 7-year-olds and two 9-year-olds). Children were recruited from a database of parents who, at the time of their children's birth, consented to be contacted at a later date about participation in developmental studies. The adults were students at McMaster University who participated in exchange for course credit or payment. Prior to the beginning of the experiment, verbal assent to participate was obtained from children in addition to written consent from their parents. Adult participants provided written consent. The study was cleared by the McMaster Research Ethics Board and conformed to the Tri-Council Statement on Ethical Conduct of Research Involving Humans (TCPS2; Canada).

Apparatus and stimuli

The experiment was conducted in a dimly lit room. The auditory stimuli were 10-ms peak-to-peak white noise bursts with a flat amplitude envelope and 2-ms on- and off-ramping. Auditory stimuli were presented from closed-ear headphones (Sennheiser HAD-200) at 107 dB SPL (measured with a Brüel & Kjær artificial ear Type 4152 and a Brüel & Kjær sound level meter Type 2270). The tactile stimuli were taps with 10 ms duration and were delivered using one of two custom-made tap devices. The first machine consisted of a dull metal pin mounted on a solenoid. The second machine was introduced after the first machine became inoperable and used an electromagnetic solenoid driving a dull tactile stimulator from tactile stimulator (Dancer Design, http://dancerdesign.co.uk/products) mounted in a wooden plank. Both machines, when activated, indented the right index finger well above detection threshold, displacing the skin by approximately 3 mm. About two thirds (13/20) of the data from each group were collected with the first machine. Both the auditory and tactile stimuli were generated and controlled by MATLAB (MathWorks) and the Psychtoolbox-3 package (Brainard, 1997).

To reduce the possibility of the noise produced by the tap device influencing the perception of the auditory stimuli, free-field white noise was played continuously during the experiment (measuring 73 dB SPL at the ear while wearing headphones). In addition, the tactile devices were mounted inside a sound-attenuating box constructed from sound-dampening ceiling tile lined with shag carpet.

Design and procedure

Two factors were manipulated: age (7-, 9-, and 11-year-old children and adults) and SOA (−1200, −800, −400, −300, −200, −100, 0, 100, 200, 300, 400, 800, and 1200). Negative values of SOA indicate that the auditory stimulus preceded the tactile stimulus, whereas positive values indicate that the auditory stimulus lagged the tactile stimulus. The onset timing and duration of auditory and tactile stimuli at all SOAs were verified using an oscilloscope. In the main experiment, each SOA was tested twice in each of 10 blocks, giving rise to a total of 260 trials.

Participants were instructed to sit facing forward and to keep their eyes closed throughout the experiment. The experimenter was present in the room and verified adherence to these instructions. Participants rested their right index finger over the tactile device, which was positioned approximately 40 cm away from their body along the axis of their midline. Participants were asked to say "yes" if they perceived that the tap and beep were presented at the same time or to say "no" if they perceived that the two stimuli were presented at different times. The experimenter keyed the responses into the computer manually and initiated the next trial.

Two practice sessions were completed prior to the main experiment. The first practice session consisted of 8 trials: 4 with large SOAs (−1200, −800, 800, and 1200) interspersed randomly with 4 0-ms SOAs. Participants were required to achieve 85% accuracy (maximum of one error; three attempts allowed) to participate in the main experiment. The second practice session included 1 trial at each of the 13 SOAs used in the main experiment in order to familiarize participants with the entire set of stimuli. This second session, as well as the main experiment, had no accuracy requirement and no feedback except for general encouragement. Children were encouraged to take frequent breaks between blocks, whereas adult participants were encouraged to request a break if needed. Not including breaks, the experiment took approximately 40 min to complete for both children and adults.

Results

Proportion of simultaneous responses

The mean proportion of simultaneous responses was calculated for each participant at each SOA. The data were submitted to a three-way analysis of variance (ANOVA) with age (7-, 9-, 11-year-olds or adults) and machine (in-house built stimulator or Dancer Design tactor) as the between-participant factors, and SOA as the within-participant factor. The factor of machine produced no significant effect or any interaction (all $ps > .05$). As such, all subsequent analyses were based on a two-way ANOVA with the factors of age and SOA (see Fig. 1). The Huynh–Feldt estimate of sphericity was used to adjust the p values of this test because of the inclusion of the within-participant factor SOA. Both factors revealed significant main effects: age, $F(3, 76) = 8.53$, $p < .001$, $\eta_p^2 = 0.25$; SOA, $F(5, 362) = 347.92$, $p < .001$, $\eta_p^2 = 0.82$. Most important, the age × SOA interaction was significant, $F(15, 362) = 4.66$, $p < .001$, $\eta_p^2 = 0.16$. A total of 13 one-way ANOVAs—1 at each SOA—were conducted (see Table 1). The main effect of age was significant at 12 of 13 SOAs (all but the−100-ms SOA). Post hoc Dunnett tests (two-tailed) were used to compare each child age group with the adult group at the 12 SOAs (see Table 1). These tests showed that 7-year-olds differed significantly from adults ($ps < .05$) at all but 3 SOAs (−100, 100, and 200 ms), whereas 9-year-olds differed significantly from adults at only 2 SOAs (−1200 and 100 ms). There were no significant differences for 11-year-olds.

Estimated parameters of simultaneity judgments

To estimate the PSS and the width of the temporal simultaneity window, each individual's data were fitted in MATLAB using a bootstrap curve-fitting routine for the simultaneity judgment task (Alcalá-Quintana & García-Pérez, 2013). One strength of this model is that the parameters associated with sensory processing speeds, sensory processing variability, and response errors (e.g., lapses in attention and/or motor response errors) are isolated in order to produce the most accurate estimates of PSS and sensitivity. This approach, first proposed by García-Pérez and Alcalá-Quintana (2012a), was formulated using an independent-channels model (Sternberg & Knoll, 1973), which assumes that signals in each modality (in this case audition and touch) are processed independently before arriving at a central comparator. For each sensory signal, the peripheral processing time and variance from each sensory pathway are estimated using an exponential distribution. The arrival time difference between the two signals at the central comparator (i.e., perceived onset time differences) then forms a bilateral exponential distribution. The arrival time difference is compared against the observer's sensitivity to determine whether a simultaneous response will be made.

In this model, at each SOA a processing time difference between the auditory and tactile stimuli is estimated ($\tau = \tau A - \tau T$), whereas the processing variabilities of the auditory and tactile systems are estimated as λA and λT, respectively. The estimated sensitivity parameter (δ) is the criterion of simultaneity judgments; if the difference of the perceived onsets is smaller than δ, then the observer would make a simultaneous response. The estimated sensitivity parameter (δ) is defined as half the width of the simultaneity window when the simultaneous response criterion is set to 50% on both the auditory- and tactile-leading sides. A low sensitivity (large value of δ) describes a wide simultaneity window; conversely, a high sensitivity (small value of δ) describes a narrow simultaneity window such that

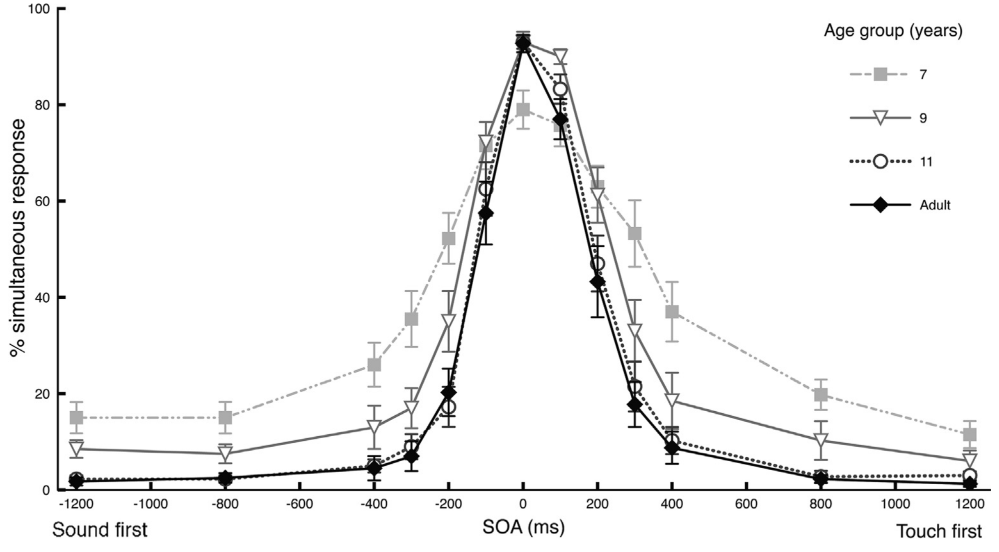

Fig. 1. Mean proportion of simultaneous responses at each stimulus onset asynchrony (SOA) for each of the four age groups. Error bars are ±1 standard error of the mean.

Table 1
Mean percentage of simultaneous responses for each age group and results of one-way ANOVAs, and post hoc tests.

SOA (ms)	Age group				$F(3, 79)$	p	η_p^2	Post hoc tests
	7 years	9 years	11 years	Adults				
−1200	15.0	8.5	2.3	1.75	10.09	<.001	.29	7 > adults**; 9 > adults*
−800	15.0	7.5	2.3	2.5	8.78	<.001	.26	7 > adults**
−400	26.0	13.0	5.0	4.5	8.17	<.001	.24	7 > adults**
−300	35.5	17.0	9.0	7.0	10.03	<.001	.28	7 > adults**
−200	52.3	35.0	17.3	20.3	9.46	<.001	.27	7 > adults**
−100	71.5	72.3	62.5	57.5	1.79	=.16	.07	
0	79.0	93.0	93.0	92.8	7.56	<.001	.23	7 < adults**
100	75.8	90.0	83.3	77.0	3.57	<.05	.12	9 > adults*
200	63.0	61.3	47.0	43.3	2.83	<.05	.10	
300	53.3	33.0	21.5	17.8	7.37	<.001	.23	7 > adults**
400	37.0	18.5	10.3	8.8	7.36	<.001	.23	7 > adults**
800	19.8	10.3	2.8	2.3	9.46	<.001	.27	7 > adults**
1200	11.5	6.0	3.0	1.3	5.90	<.005	.19	7 > adults**

Note. Dunnett test was used to determine the proportion simultaneous at each SOA. Negative SOAs indicate that the sound was presented first, and positive SOAs indicate that the tap was presented first.
* $p < .05$.
** $p < .01$.

the observer has the precision necessary to resolve small differences in stimulus arrival latencies. The PSS was computed as the midpoint of the full width of the temporal simultaneity window. Three response error parameters were also estimated: responding "simultaneous" to either auditory-leading trials (ϵAF) or tactile-leading trials (ϵTF) or responding "not simultaneous" at the 0-ms SOA (ϵS). By accounting for the response errors, the model can make more precise estimates of both the perceptual and sensory parameters.

A one-way ANOVA on the estimates of sensitivity with a between-participant factor of age (see Table 2) revealed a significant main effect, $F(3, 76) = 4.59$, $p < .01$, $\eta_p^2 = 0.05$. Each age group was compared with adults with a post hoc Dunnett test (one-tailed). The 7-year-olds had larger δ values

Table 2
Mean (and standard error) of each estimated parameter from the simultaneity judgment task.

Parameter	Age group				$F(3, 76)$	p	η_p^2	Post hoc tests
	7 years	9 years	11 years	Adults				
δ	271.7 (27.0)	228.6 (25.7)	172.3 (13.6)	174.7 (20.0)	4.59	<.01	.05	7 > adults**
PSS	57.4 (21.2)	56.2 (12.6)	38.5 (6.3)	35.3 (8.0)	0.75	= .53	.15	
λA	0.17 (0.06)	0.15 (0.07)	0.34 (0.09)	0.19 (0.07)	1.28	= .29	.05	
λT	0.15 (0.06)	0.21 (0.06)	0.11 (0.05)	0.21 (0.07)	0.59	= .63	.02	
τ	−64.2 (31.8)	−72.6 (21.8)	−40.4 (15.5)	−40.5 (14.4)	0.56	= .64	.02	
εAF	0.15 (0.03)	0.08 (0.02)	0.02 (0.01)	0.02 (<0.01)	11.62	<.001	.31	7 > adults**; 9 > adults*
εS	0.11 (0.03)	0.04 (0.01)	0.02 (0.01)	0.04 (0.02)	3.92	<.05	.13	7 > adults**
εTF	0.14 (0.03)	0.08 (0.02)	0.03 (0.01)	0.02 (0.01)	7.37	<.001	.23	7 > adults**; 9 > adults*

Note. Results of one-way ANOVAs and post hoc tests (Dunnett) were used. δ, resolution (threshold of simultaneity perception); PSS, point of subjective simultaneity; λA, processing variability of auditory stimulus; λT, processing variability of tactile stimulus; τ, processing time difference between auditory and tactile stimulus ($\tau A - \tau T$); εAF, response errors in the auditory-leading trials; εS, response errors in the simultaneous trials; εTF, response errors in the tactile-leading trials.
* $p < .05$.
** $p < .01$.

($p < .005$), indicating lower sensitivity. A similar trend was observed for the 9-year-olds, although this comparison was not significant ($p = .11$). The δ was similar between the 11-year-olds and adults ($p = .78$) (see Fig. 2A).

The PSS, corresponding to the midpoint of the audiotactile simultaneity window, was on the tactile-leading side for all age groups: 7-year-olds, $t(19) = 2.70$, $p < .05$, Cohen's $d = 0.60$; 9-year-olds, $t(19) = 4.45$, $p < .001$, Cohen's $d = 1.00$; 11-year-olds, $t(19) = 6.12$, $p < .001$, Cohen's $d = 1.37$; adults, $t(19) = 4.43$, $p < .001$, Cohen's $d = 0.99$. A one-way ANOVA revealed no effect of age ($p = .53$). The PSS located at the tactile-leading side in all four age groups suggests that the simultaneity window became wider on the touch-leading side than on the auditory-leading side before 7 years, the youngest group tested (see Fig. 2B).

No age effect was found for the three sensory processing parameters: auditory processing variability (λA), tactile processing variability (λT), and processing arrival time difference (τ) (all *ps* > .25). Thus, sensory processing for these stimuli was adult-like by 7 years of age. The parameter of processing time difference ($\tau = \tau A - \tau T$) was negative and significantly different from zero in 9-year-olds, $t(19) = -3.33$, $p < .01$, Cohen's $d = 0.74$; 11-year-olds, $t(19) = -2.61$, $p < .05$, Cohen's $d = 0.58$; and adults, $t(19) = -2.81$, $p < .05$, Cohen's $d = 0.63$, with the same trend in 7-year-olds, $t(19) = -2.02$, $p = .06$, Cohen's $d = 0.45$. The negative τ in all age groups suggests that the auditory signal reaches the central comparator prior to the tactile signal when the onset of the two signals is at the same time.

Each of the response error parameters was submitted to a one-way ANOVA with the factor age; post hoc tests used a one-tailed Dunnett test. Auditory-leading (ϵAF), tactile-leading (ϵTF), and simultaneous (ϵS) response errors varied with age, $F(3, 76) = 11.62$, $p < .001$, $\eta_p^2 = 0.31$; $F(3, 76) = 7.37$, $p < .001$, $\eta_p^2 = 0.23$; and $F(3, 76) = 3.92$, $p = .01$, $\eta_p^2 = 0.13$, respectively. When the auditory or tactile stimulus was leading, 7-year-olds (*ps* < .001) and 9-year-olds (*ps* < .05) made more errors than adults, whereas 11-year-olds did not ($p = .35$ for auditory leading and $p = .29$ for tactile leading). When the stimuli were simultaneous (ϵS), only the 7-year-olds showed a higher error rate ($p < .01$); the 9-year-olds ($p = .33$) and 11-year-olds ($p = .45$) were not different from adults. In sum, 7-year-olds made more errors in all three conditions, 9-year-olds made more errors only when the stimuli were nonsimultaneous, and 11-year-olds made as few errors as adults under all three conditions.

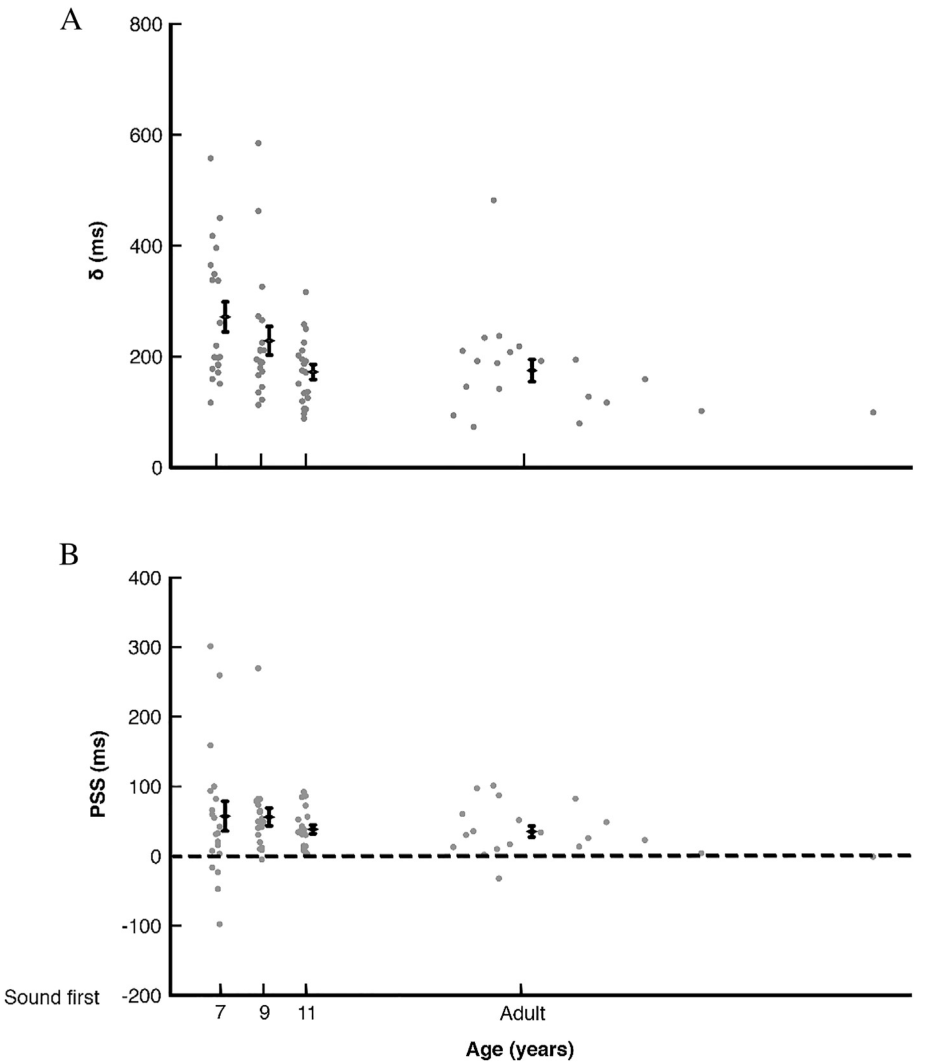

Fig. 2. The threshold of simultaneity perception (δ) (A) and point of subjective simultaneity (PSS) (B) as a function of age. The mean PSS in each age group was positive, indicating the conditions where the tactile stimulus was presented first. Gray dots represent individual data, black dots represent the mean for each age group, and error bars indicate ±1 standard error of the mean.

Discussion

The current study charted the developmental trajectory of the perception of audiotactile simultaneity by testing three groups of children (7-, 9-, and 11-year-olds) and adults. The PSS was tactile leading in all age groups, even at the youngest age tested. However, children differed from adults on many other measures. Children aged 7 years made more simultaneous responses across a wide range of SOAs, whereas children aged 9 years did so only at the -1200- and 100-ms SOAs. Based on an instantiation of the independent-channels model for stimulus temporal judgments (García-Pérez & Alcalá-Quintana, 2012a), 7-year-olds had a significantly wider simultaneity window (i.e., larger δ) and a significantly higher rate of response errors in the sound-leading, tap-leading, and simultaneous conditions. Children aged 9 years were still not adult-like on some of the parameters measured; compared with adults, 9-year-olds made more response errors when either the sound or tap led. Taken together, children aged 11 years have reached adult-level performance across all measures obtained from the simultaneity judgment task for audiotactile stimuli.

Children aged 7 years have not yet reached adult-like precision for the perception of audiotactile simultaneity. Specifically, the temporal simultaneity window was significantly wider (i.e., larger δ) for 7-year-olds compared with adults. In other words, these children likely perceive temporally close stimuli as originating from a single event, whereas adults may attribute the same pair of stimuli to different sources. The audiotactile simultaneity window was not statistically wider for 9-year-olds than for adults; however, qualitative observation of the data suggests that some children at this age have much wider simultaneity windows, highlighting the importance of considering individual differences during development (see Fig. 2A). Thus, it appears that 9-year-olds are in a transitional stage toward reaching perceptual maturity.

Children aged 7 and 9 years also made more response errors than adults. In the parameter estimation model used here (García-Pérez & Alcalá-Quintana, 2012a), response errors represent participants' lapses in attention and mistakes in motor responses. Thus, the higher response errors in 7- and 9-year-olds suggest an immature system of executive and attentional control. The reduction in response errors to adult levels by 11 years of age is consistent with the literature on the maturation of these systems during late childhood (see Ridderinkhof, van der Molen, Band, & Bashore, 1997; Rueda et al., 2004; Shore, Burack, Miller, Joseph, & Enns, 2006).

For all ages tested in the current study, the PSS was shifted toward the tactile-leading side, suggesting that the tap and beep were most likely to be perceived as simultaneous when the tap was presented slightly before the beep. The shifts in the PSS may result from at least three sources of time differences: physical signal propagation time in the environment, sensory transduction latency at the receptor, and/or neural transmission time to a central comparator (Stein & Meredith, 1993; Stone et al., 2001). In the current study, the propagation times for the auditory and tactile signals are negligible and essentially the same as each other (sound presented via headphones directly to the ear and tap administered directly to the skin of the fingertip). Sensory transduction latency, in which physical signals are transduced into neural impulses, is also similar for the auditory and tactile modalities given the mechanical nature of the receptor mechanism. Thus, the observed shift of the PSS to the tactile-leading side most likely originates in the differential neural transmission time from the receptors (hair cells in the tympanic membrane vs. mechanoreceptors in the fingertip) to the brain (Barnett-Cowan & Harris, 2009; Stein & Meredith, 1993). To be clear, the tactile stimulus must be earlier than the auditory stimulus because the neural signal has farther to travel (see also Fujisaki & Nishida, 2009; Zampini et al., 2005). The similarity in PSS across the ages tested implies one of two things: either that changes in arm length do not significantly change the time of neural transmission (perhaps because increased myelination speeds up the neural transmission time with age) or that the perceptual system continuously recalibrates to temporal changes as the arms grow (see Ernst, 2008). Critically, the constancy of PSS across development in the face of the aforementioned developmental trajectory for the temporal simultaneity window implies that the specific mechanisms underlying these two measures (PSS and sensitivity) are independent.

In summary, the overall flatter and wider simultaneity judgment curve for 7-year-olds than for adults can be attributed to the young children's immature sensitivity to audiotactile simultaneity, poor response execution, and poor attentional control. Children aged 9 years appear to be in transition between the immature 7-year-olds and the mature 11-year-olds. The 9-year-olds showed greater individual variability in their sensitivity to audiotactile simultaneity and made more errors than adults. In contrast, children aged 11 years performed like adults on all measures and estimated parameters examined.

Comparison across modality pairings

The perception of audiovisual simultaneity develops earlier than that of visuotactile and audiotactile simultaneity (Chen et al., 2016, 2018; current study; see Fig. 3). This may derive from the ubiquitous use of audiovisual cues in everyday life, beginning during infancy and continuing throughout life.

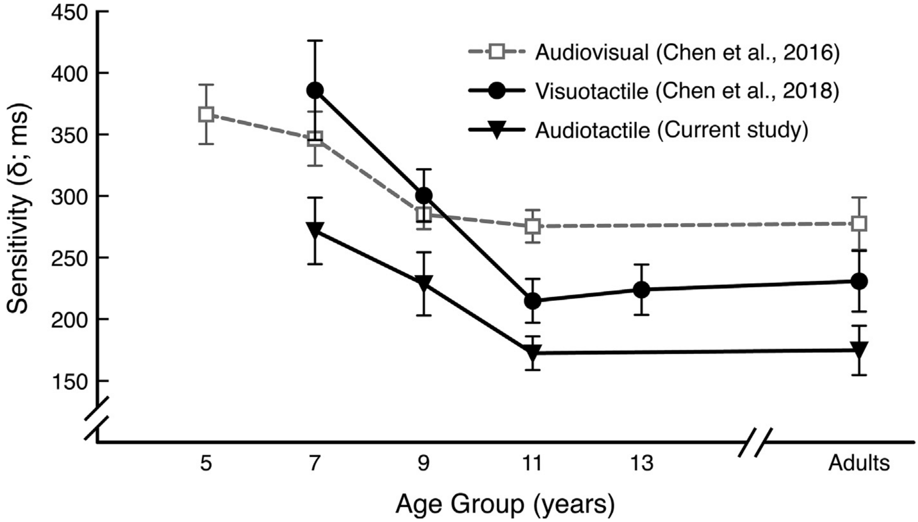

Fig. 3. Mean sensitivity (δ) corresponding to half of the width of the temporal simultaneity window for the current audiotactile data compared against audiovisual and visuotactile simultaneity perception. Error bars are ±1 standard error of the mean.

Specifically, infants demonstrate a rudimentary ability to discriminate the synchrony of auditory and visual stimuli at birth (Lewkowicz et al., 2010). Subsequently, the bulk of language acquisition occurs during early childhood (Bornstein, Hahn, & Haynes, 2004; Vihman, 1996), and speech comprehension requires a combination of auditory and visual signals (Bristow et al., 2009; Chuen & Schutz, 2016; McGurk & MacDonald, 1976; Van Wassenhove, Grant, & Poeppel, 2007; Vatakis, & Spence, 2007, 2008; Weatherhead & White, 2017). In contrast, beyond infancy, interactions between touch and vision or touch and audition are not as pertinent for everyday function and social interactions.

Alternatively, the earlier maturation of adult-like precision in perceiving audiovisual simultaneity than of those pairings involving touch may derive from the unique body-based nature of tactile processing. Tactile signals are first encoded in a somatotopic frame of reference and are then translated into an environmental frame of reference (Azañón & Soto-Faraco, 2008; Heed & Azañón, 2014; Shore, Spry, & Spence, 2002), whereas visual and auditory signals are represented in an environmental frame of reference from the start of their processing. Such coordination between somatosensory and environmental frames of reference continues throughout development but differs between childhood and puberty. Specifically, during childhood the size of the body and limbs change nonlinearly while the size of the head remains stable, and then during puberty the body, limbs, and head grow proportionally (see Bremner, Holmes, & Spence, 2012, for a review). Significant cognitive improvement in the coordination between the internal (somatotopic) and external (environmental) frames of reference, specifically in terms of visual perspective taking and body ownership, also occurs around the same ages during late childhood (see Pearson, Marsh, Ropar, & Hamilton, 2016). Hence, the protracted development of the perception of visuotactile and audiotactile simultaneity may be caused in part by the need to coordinate changing frames of reference until the end of childhood. In contrast, the coordination between vision and audition may be completed earlier because they use the same frame of reference.

A third possibility arises from the travel distances of neural signals from sensory organs to the brain and how they change with body growth. Specifically, auditory and visual signals need to travel a short distance (i.e., cochlea to the temporal cortex and retina to the occipital cortex), which does not change significantly across development. In contrast, tactile neural signals need to travel from the receptors on the skin of the finger to the brain; this distance is longer and changes considerably as the body grows. Although this had no effect on the PSS, the required recalibration may prevent a fixed and stable temporal simultaneity window from developing until relative growth rates become proportional. Consistent with this extended flexibility, we note that unisensory temporal resolution for touch matures later (perhaps by 6 years of age; see Pagel, Heed, & Röder, 2009) than for vision (by 4 years of age; Ellemberg, Lewis, Liu, & Maurer, 1999) or audition (by 4 years of age; Wightman, Allen, Dolan, Kistler, & Jamieson, 1989). Thus, we propose that the perceptual system constantly recalibrates the perceived onset of tactile stimuli but does not crystalize the temporal simultaneity window for this modality until the body grows proportionately.

Note that the three explanations are not mutually exclusive but rather more likely to contribute conjointly to the development of the perception of multisensory simultaneity. Other nonphysiological factors such as the development of executive functioning, cognitive complexity, and decision making may also influence the developmental trajectories of simultaneity perception. Regardless, audiovisual interactions appear to be privileged in terms of perceptual maturation, likely because of the extensive daily occurrences of audiovisual events. In contrast, the challenge of coordination and recalibration of spatial and temporal representation or processing across sensory modalities during body growth may lead to the longer developmental trajectories for audiotactile and visuotactile than for audiovisual simultaneity perception.

Single or multiple mechanisms for multisensory simultaneity perception

The different developmental trajectories described above suggest unique mechanisms for each modality pairing rather than a unitary mechanism for all pairings (see also Harrar & Harris, 2005, 2008; Van der Burg, Alais, & Cass, 2013; but see Hanson, Heron, & Whitaker, 2008; Machulla, Di Luca, & Ernst, 2016). Studies of temporal recalibration (see Van der Burg et al., 2013) provide another example supporting unique mechanisms. Audiovisual recalibration can occur on a trial-by-trial basis, whereas perception of visuotactile and audiotactile pairings recalibrates at a slower timescale (Van der Burg, Alais, & Cass, 2015; Van der Burg, Orchard-Mills, & Alais, 2015). This difference may arise because audiovisual signals occur external to the body and temporal recalibration must account for the constant changes in the distance of the signals (Engel & Dougherty, 1971; Sugita & Suzuki, 2003; see Vroomen & Keetels, 2010, for a review). Audiotactile and visuotactile signals, however, originate on the body surface, and so their propagation time differences (from stimulus origin to sensory receptors) are relatively constant, and recalibration might not need to occur on a rapid timescale. A third piece of evidence comes from studies of temporal perception in a population of adults treated for congenital cataracts (Chen, Lewis, Shore, & Maurer, 2017). These individuals were born fully deprived of patterned vision in either one eye or both eyes because of a dense cataract or cataracts. In developed countries, full vision is typically restored within the first 6 months of life through the removal of the cataractous lens followed by the use of corrective lenses. When tested as adults, these patients show deficits in the perception of audiovisual simultaneity, whereas the perception of visuotactile simultaneity is spared (Chen et al., 2017). These findings further support the claim that different mechanisms are involved in the perception of simultaneity for different modality pairings.

That said, it remains unclear the extent to which the perception of visuotactile simultaneity and that of audiotactile simultaneity share the same process or mechanism. Current evidence shows that they mature at the same age (Chen et al., 2018; current study). Nevertheless, testing groups in finer age categories may reveal subtle developmental differences. In addition, examining the influence of transient early visual deprivation on audiotactile temporal perception in cataract-reversal patients should provide additional evidence on the extent to which the perceptions of audiovisual, visuotactile, and audiotactile simultaneity are mediated by overlapping or separate underlying mechanisms.

Relation between simultaneity perception and multisensory integration

Two distinct processes contribute to our coherent perception of multisensory events. One determines whether two signals presented to different modalities originate from the same event, known as the unity assumption (cf. Chen & Spence, 2017) or the unity prior in the process of causal inference (e.g., Odegaard & Shams, 2016; Odegaard, Wozny, & Shams, 2017). In this process, temporal coincidence provides a critical cue that two signals should be integrated into a single percept (Stein & Meredith, 1993; see Vroomen & Keetels, 2010, for a review). The other process follows the rules of multisensory optimal integration by weighing each sensory signal in terms of its reliability (e.g., Alais & Burr, 2004; Ernst & Banks, 2002; Ernst & Bülthoff, 2004). A comparison of the developmental trajectories of temporal perception and multisensory integration provides insight into the relation between these two processes. To the best of our knowledge, the only studies to examine the development of audiotactile integration demonstrated that 11-year-olds did not integrate audiotactile cues associated with object size (e.g., bigger object makes louder sound when hitting the floor) as optimally as adults (Petrini, Remark, Smith, & Nardini, 2014), and children aged 13–15 years are still in a transitional stage (Scheller, Proulx, & Petrini, 2018). In the context of the current findings of adult-like perception of audiotactile simultaneity by 11 years of age, we might propose that the maturation of simultaneity perception is a prerequisite for optimal integration, at least for the audiotactile pairing. In other words, one may assume that unity must be established before accurate, or optimal, multisensory integration can occur (e.g., Welch & Warren, 1980).

Examinations of other modality pairings, however, present a different and more complex picture. The development of audiovisual optimal integration appears to be adult-like by 8 years of age in the temporal domain (the youngest age tested; see Adams, 2016, for evidence of optimal integration emerging at 10 years of age), whereas adult-like integration does not emerge until after 12 years of age in the spatial domain (the oldest age tested; Gori, Sandini, & Burr, 2012). In contrast, the maturation of the perception of audiovisual simultaneity occurs between these two ages, by 9 years (Chen et al., 2016). The optimal integration for visuotactile shape and orientation perception matures at around 8–10 years of age, similar to the maturation of visuotactile simultaneity perception (by 11 years; Chen et al., 2018). Thus, the order in which simultaneity perception and optimal integration reach maturity differs depending on the sensory pairing and the stimulus domain(s) under examination.

The above findings seem to suggest that the developmental trajectories of multisensory simultaneity perception and optimal integration might not be sequential. However, the nature of the tasks used to measure simultaneity perception and optimal integration does not support direct comparisons to test whether temporal perception and multisensory integration are sequential or interdependent. The only way to properly compare the maturation of temporal perception and optimal integration across modality pairings would require using the same stimuli to measure both abilities using tasks with similar demands. Consequently, the only statement that can be made with any degree of certainty is that the development of multisensory simultaneity perception and optimal integration are prolonged into late childhood or early adolescence for all modality pairings.

Conclusions

This is the first study to measure the developmental trajectory of the perception of audiotactile simultaneity—a modality combination that has rarely been studied to date. Children younger than 11 years had wider windows of simultaneity perception and were likely to make response errors. The PSS, on the other hand, was shifted to the tactile-leading side by 7 years, the youngest age tested. The later developmental trajectories for the perception of audiotactile and visuotactile simultaneity than for audiovisual simultaneity, in combination with evidence from cataract-reversal patients, suggest different underlying processes of simultaneity perception for different modality pairings.

Acknowledgments

D.I.S. was funded by a Discovery grant from the Natural Sciences and Engineering Research Council of Canada (NSERC), and D.M. was funded by the James S. McDonnell Foundation and NSERC. We thank Sally Stafford, Miroslav Cika, and Lisa Lorentz for their administrative, technical, and editing contributions, respectively. We also thank Sehar Arfeen, Mathew Klein, Katherine Silang, Kaitlyn Gonsalves, Michelle Ho, Lesley Tsui, and Diana Chu for all their help with recruiting and data collection.

References

Adams, W. J. (2016). The development of audio–visual integration for temporal judgements. *PLoS Computational Biology, 12*(4), e1004865.

Alais, D., & Burr, D. (2004). The ventriloquist effect results from near-optimal bimodal integration. *Current Biology, 14*, 257–262.

Alcalá-Quintana, R., & García-Pérez, M. A. (2013). Fitting model-based psychometric functions to simultaneity and temporal-order judgment data: MATLAB and R routines. *Behavior Research Methods, 45*, 972–998.

Azañón, E., & Soto-Faraco, S. (2008). Changing reference frames during the encoding of tactile events. *Current Biology, 18*, 1044–1049.

Barnett-Cowan, M., & Harris, L. R. (2009). Perceived timing of vestibular stimulation relative to touch, light and sound. *Experimental Brain Research, 198*, 221–231.

Bornstein, M. H., Hahn, C. S., & Haynes, O. M. (2004). Specific and general language performance across early childhood: Stability and gender considerations. *First Language, 24*, 267–304.

Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision, 10*, 433–436.

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. K. Lewkowicz, & C. Spence (Eds.), *Multisensory development* (pp. 113–136). Oxford, UK: Oxford University Press.

Bristow, D., Dehaene-Lambertz, G., Mattout, J., Soares, C., Gliga, T., Baillet, S., & Mangin, J. F. (2009). Hearing faces: How the infant brain matches the face it sees with the speech it hears. *Journal of Cognitive Neuroscience, 21*, 905–921.

Chen, Y.-C., Lewis, T. L., Shore, D. I., & Maurer, D. (2017). Early binocular input is critical for development of audiovisual but not visuotactile simultaneity perception. *Current Biology, 27*, 583–589.

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.

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.

Chen, Y.-C., & Spence, C. (2017). Assessing the role of the "unity assumption" on multisensory integration: A review. *Frontiers in Psychology, 8*. https://doi.org/10.3389/fpsyg.2017.00445.

Chuen, L., & Schutz, M. (2016). The unity assumption facilitates cross-modal binding of musical, non-speech stimuli: The role of spectral and amplitude envelope cues. *Attention, Perception, & Psychophysics, 78*, 1512–1528.

Ellemberg, D., Lewis, T. L., Liu, C. H., & Maurer, D. (1999). Development of spatial and temporal vision during childhood. *Vision Research, 39*, 2325–2333.

Engel, G. R., & Dougherty, W. G. (1971). Visual–auditory distance constancy. *Nature, 234*, 308.

Ernst, M. O. (2008). Multisensory integration: A late bloomer. *Current Biology, 18*, R519–R521.

Ernst, M. O., & Banks, M. S. (2002). Humans integrate visual and haptic information in a statistically optimal fashion. *Nature, 415*, 429–433.

Ernst, M. O., & Bülthoff, H. H. (2004). Merging the senses into a robust percept. *Trends in Cognitive Sciences, 8*, 162–169.

Filippetti, M. L., Johnson, M. H., Lloyd-Fox, S., Dragovic, D., & Farroni, T. (2013). Body perception in newborns. *Current Biology, 23*, 2413–2416.

Fujisaki, W., & Nishida, S. Y. (2009). Audio–tactile superiority over visuo–tactile and audio–visual combinations in the temporal resolution of synchrony perception. *Experimental Brain Research, 198*, 245–259.

García-Pérez, M. A., & Alcalá-Quintana, R. (2012a). On the discrepant results in synchrony judgment and temporal-order judgment tasks: A quantitative model. *Psychonomic Bulletin & Review, 19*, 820–846.

García-Pérez, M. A., & Alcalá-Quintana, R. (2012b). Response errors explain the failure of independent-channels models of perception of temporal order. *Frontiers in Psychology, 3*. https://doi.org/10.3389/fpsyg.2012.00094.

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.

Guest, S., Catmur, C., Lloyd, D., & Spence, C. (2002). Audiotactile interactions in roughness perception. *Experimental Brain Research, 146*, 161–171.

Hanson, J. V. M., Heron, J., & Whitaker, D. (2008). Recalibration of perceived time across sensory modalities. *Experimental Brain Research, 185*, 347–352.

Harrar, V., & Harris, L. R. (2005). Simultaneity constancy: Detecting events with touch and vision. *Experimental Brain Research, 166*, 465–473.

Harrar, V., & Harris, L. R. (2008). The effect of exposure to asynchronous audio, visual, and tactile stimulus combinations on the perception of simultaneity. *Experimental Brain Research, 186*, 517–524.

Heed, T., & Azañón, E. (2014). Using time to investigate space: A review of tactile temporal order judgments as a window onto spatial processing in touch. *Frontiers in Psychology, 5*. https://doi.org/10.3389/fpsyg.2014.00076.

Hillock, A. R., Powers, A. R., & Wallace, M. T. (2011). Binding of sights and sounds: Age-related changes in multisensory temporal processing. *Neuropsychologia, 49*, 461–467.

Hillock-Dunn, A., & Wallace, M. T. (2012). Developmental changes in the multisensory temporal binding window persist into adolescence. *Developmental Science, 15*, 688–696.

Jousmäki, V., & Hari, R. (1998). Parchment-skin illusion: Sound-biased touch. *Current Biology, 8*, R190–R191.

Kaganovich, N. (2016). Development of sensitivity to audiovisual temporal asynchrony during mid-childhood. *Developmental Psychology, 52*, 232–241.

Kisilvesky, B. S., & Muir, D. W. (1991). Human fetal and subsequent newborn responses to sound and vibration. *Infant Behavior and Development, 14*, 1–26.

Lewkowicz, D. J., & Flom, R. (2014). The audiovisual temporal binding window narrows in early childhood. *Child Development, 85*, 685–694.

Lewkowicz, D. J., Leo, I., & Simion, F. (2010). Intersensory perception at birth: Newborns match nonhuman primate faces and voices. *Infancy, 15*, 46–60.

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*, 1026–1038.
McGurk, H., & MacDonald, J. (1976). Hearing lips and seeing voices. *Nature, 264*, 746–748.
Morrongiello, B. A., Fenwick, K. D., & Chance, G. (1998). Crossmodal learning in newborn infants: Inference about properties of auditory–visual events. *Infant Behavior and Development, 21*, 543–553.
Occelli, V., Spence, C., & Zampini, M. (2011). Audiotactile interactions in temporal perception. *Psychonomic Bulletin & Review, 18*, 429–454.
Odegaard, B., & Shams, L. (2016). The brain's tendency to bind audiovisual signals is stable but not general. *Psychological Science, 27*, 583–591.
Odegaard, B., Wozny, D. R., & Shams, L. (2017). A simple and efficient method to enhance audiovisual binding tendencies. *PeerJ, 5*, e3143.
Pagel, B., Heed, T., & Röder, B. (2009). Change of reference frame for tactile localization during child development. *Developmental Science, 12*, 929–937.
Pearson, A., Marsh, L., Ropar, D., & Hamilton, A. (2016). Cognitive mechanisms underlying visual perspective taking in typical and ASC children. *Autism Research, 9*, 121–130.
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*, 376–387.
Ridderinkhof, K. R., van der Molen, M. W., Band, G. P., & Bashore, T. R. (1997). Sources of interference from irrelevant information: A developmental study. *Journal of Experimental Child Psychology, 65*, 315–341.
Röder, B., Pagel, B., & Heed, T. (2013). The implicit use of spatial information develops later for crossmodal than for intramodal temporal processing. *Cognition, 126*, 301–306.
Rueda, M. R., Fan, J., McCandliss, B. D., Halparin, J. D., Gruber, D. B., Lercari, L. P., & Posner, M. I. (2004). Development of attentional networks in childhood. *Neuropsychologia, 42*, 1029–1040.
Scheller, M., Proulx, M. J., & Petrini, K. (2018). Audio-haptic cue integration across the lifespan. *Poster presented at the 19th annual international multisensory research forum, Toronto, Ontario, Canada*.
Shore, D. I., Burack, J. A., Miller, D., Joseph, S., & Enns, J. T. (2006). The development of change detection. *Developmental Science, 9*, 490–497.
Shore, D. I., Spry, E., & Spence, C. (2002). Confusing the mind by crossing the hands. *Cognitive Brain Research, 14*, 153–163.
Soto-Faraco, S., & Deco, G. (2009). Multisensory contributions to the perception of vibrotactile events. *Behavioural Brain Research, 196*, 145–154.
Stein, B. E., & Meredith, M. A. (1993). *The merging of the senses*. Cambridge, MA: MIT Press.
Sternberg, S., & Knoll, R. L. (1973). The perception of temporal order: Fundamental issues and a general model. *Attention and Performance IV, 4*, 629–685.
Stevenson, R. A., Baum, S. H., Krueger, J., Newhouse, P. A., & Wallace, M. T. (2018). Links between temporal acuity and multisensory integration across lifespan. *Journal of Experimental Psychology: Human Perception and Performance, 44*, 106–116.
Stone, J. V., Hunkin, N. M., Porrill, J., Wood, R., Keeler, V., Beanland, M., ... Porter, N. R. (2001). When is now? Perception of simultaneity. *Proceedings of the Royal Society of London B: Biological Sciences, 268*, 31–38.
Sugita, Y., & Suzuki, Y. (2003). Implicit estimation of sound-arrival time. *Nature, 421*, 911.
Van der Burg, E., Alais, D., & Cass, J. (2013). Rapid recalibration to audiovisual asynchrony. *Journal of Neuroscience, 33*, 14633–14637.
Van der Burg, E., Alais, D., & Cass, J. (2015). Audiovisual temporal recalibration occurs independently at two different time scales. *Scientific Reports, 5*, 14526.
Van der Burg, E., Orchard-Mills, E., & Alais, D. (2015). Rapid temporal recalibration is unique to audiovisual stimuli. *Experimental Brain Research, 233*, 53–59.
Van Wassenhove, V., Grant, K. W., & Poeppel, D. (2007). Temporal window of integration in auditory–visual speech perception. *Neuropsychologia, 45*, 598–607.
Vatakis, A., & Spence, C. (2007). Crossmodal binding: Evaluating the "unity assumption" using audiovisual speech stimuli. *Perception & Psychophysics, 69*, 744–756.
Vatakis, A., & Spence, C. (2008). Evaluating the influence of the "unity assumption" on the temporal perception of realistic audiovisual stimuli. *Acta Psychologica, 127*, 12–23.
Vihman, M. M. (1996). *Phonological development: The origins of language in the child*. Cambridge, MA: Blackwell.
Vroomen, J., & Keetels, M. (2010). Perception of intersensory synchrony: A tutorial review. *Attention, Perception, & Psychophysics, 72*, 871–884.
Weatherhead, D., & White, K. S. (2017). Read my lips: Visual speech influences word processing in infants. *Cognition, 160*, 103–109.
Welch, R. B., & Warren, D. H. (1980). Immediate perceptual response to intersensory discrepancy. *Psychological Bulletin, 88*, 638–667.
Wightman, F., Allen, P., Dolan, T., Kistler, D., & Jamieson, D. (1989). Temporal resolution in children. *Child Development, 60*, 611–624.
Zampini, M., Brown, T., Shore, D. I., Maravita, A., Röder, B., & Spence, C. (2005). Audiotactile temporal order judgments. *Acta Psychologica, 118*, 277–291.