The Development of Temporal Resolution: Between-Channel Gap Detection in Infants and Adults

Nicholas A. Smith
Laurel J. Trainor
David I. Shore
McMaster University, Hamilton, Ontario, Canada

Purpose: Infants have a good ability to detect brief silent gaps between 2 short identical sound markers (within-channel gap detection), with thresholds between 2 and 11 ms. The present experiment traces the development of temporal resolution for between-channel gaps (i.e., gaps delineated by spectrally disparate markers). This ability appears crucial for the perception of complex stimuli such as speech and is thought to reflect more central auditory processing.
Method: Infants age 6–7.5 months and adults were tested in a between-channel gap detection task using a conditioned head-turn procedure. Gaps were marked by 1- and 4-kHz Gaussian-enveloped sine-tone markers.
Results: Infant gap thresholds were between 30 and 40 ms under conditions in which adult thresholds were between 10 and 20 ms.
Conclusions: Unlike within-channel gap detection, the central temporal processing required for between-channel gap detection is still immature at 6 months of age.

KEY WORDS: infants, adults, psychoacoustics, hearing assessment

The ability to resolve fine temporal information in sound is crucial for the understanding of speech and other complex auditory stimuli. Poor temporal processing in older children and adults may be related to poor language and/or reading skills (Farmer & Klein, 1995; Tallal, Stark, & Mellits, 1985). Furthermore, temporal resolution measured in infancy may predict early language skills (Benasich & Tallal, 2002; Trehub & Henderson, 1996). Gap detection thresholds—the shortest detectable interruption in a sound—are a widely used measure of listeners' temporal resolution. The present study compares gap thresholds in infants and adults under conditions in which the sounds preceding and following the gap are processed in different frequency channels; that is, the markers stimulate different regions of the tonotopically organized basilar membrane and subsequent frequency-selective channels in the auditory pathway.

A variety of sound markers have been used in gap detection tasks, including sinusoids (Shailer & Moore, 1987; Williams & Perrot, 1972), broadband noise (Penner, 1977; Plomp, 1964), and narrowband noise (Fitzgibbons & Wightman, 1982; Shailer & Moore, 1985). The auditory system represents each of these stimuli differently, with broadband signals activating more frequency channels or areas of the tonotopic representation than narrowband or sine-tone stimuli. Of particular interest is a comparison of within-channel gap detection tasks, for which both markers can be encoded within the same frequency channel, and between-channel tasks, for which the leading and trailing markers activate different channels (Fitzgibbons, Pollatsek, & Thomas, 1974; Phillips & Hall, 2000; Phillips, Taylor, Hall, Carr, & Mossop, 1997). For the within-channel case, gap information is present peripherally in a given frequency channel and can be recorded electrophysiologically in the auditory nerve (Zhang, Salvi, & Saunders, 1990). However, performance on a within-channel gap detection task may reflect efficiency of intensity processing rather than limits in temporal processing per se. Thresholds for detection of temporal modulation of a noise carrier (a within-channel task) decrease between 4 years of age and adulthood; however, when examining the functions relating detection threshold to modulation frequency, there is no change in the time constant, suggesting no difference across age in temporal resolution, but an improvement with age in intensity coding (Hall & Grose, 1994). In considering whether elevated backward masking in children was due to poor temporal resolution or to poor intensity coding, Hill, Hartley, Glasberg, Moore, and Moore (2004) employed a within-channel task—a 1000 Hz pure-tone signal and a masker with a noise burst centered at 1000 Hz with a bandwidth of 800 Hz. As in Hall and Grose, age differences in masking across different time delays between the signal and masker could be well modeled by improvements in intensity coding but not by differences in temporal resolution.

In contrast to within-channel temporal tasks, in between-channel tasks the offset of the first marker and the onset of the second marker are always perceived, whether or not a gap is present. Thus, an intensity difference within a channel is not a reliable cue for the presence of a gap, and detection must rely on a timing comparison between channels (Hanekom & Shannon, 1998; Oxenham, 2000). The role of different mechanisms in within-channel compared with between-channel gap detection tasks is supported by perceptual studies. Between-channel gap thresholds are considerably higher than within-channel thresholds (Fitzgibbons et al., 1974; Formby, Gerber, Sherlock, & Magder, 1998; Formby, Sherlock, & Li, 1998; Grose, Hall, Buss, & Hatch, 2001; Phillips et al., 1997; Phillips & Hall, 2000; Taylor, Hall, Boehnke, & Phillips, 1999). With cochlear implant users, gap detection thresholds increase as the markers on either side of the gap are presented to electrodes that are further apart from each other (Hanekom & Shannon, 1998). Furthermore, between-channel thresholds are only weakly related to within-channel thresholds within an individual, and show considerably greater variance across individuals in comparison to within-channel thresholds (Phillips & Smith, 2004).

By definition, between-channel gap detection—with spectrally nonoverlapping markers—must rely on central mechanisms involving comparisons between channels (Phillips & Hall, 2000), whereas within-channel detection could rely on peripheral encoding. It remains unclear as to exactly where in the auditory pathway between-channel integrations and temporal comparisons are calculated. Oxenham (2000) has demonstrated that spectral differences are more important than virtual pitch differences between markers for obtaining the elevated thresholds associated with between-channel gap tasks, suggesting that between-channel temporal comparisons are made before virtual pitch is determined. However, it remains unclear as to where in the auditory pathway a virtual pitch code is derived.

Within-channel temporal resolution has been studied in infants with various stimuli. Using a conditioned head-turn behavioral response, Trehub, Schneider, and Henderson (1995) estimated infants' thresholds to be 11 ms (adults' thresholds were 5 ms) in a within-channel gap detection task using short 500-Hz Gaussian enveloped tone pips (first described by Schneider, Pichora-Fuller, Kowalchuk, & Lamb, 1994).

Electrophysiological work suggests that within-channel gap detection is fairly mature early in life. For example, auditory brainstem responses to gaps in broadband noise suggest similar infant and adult thresholds of 2 to 3 ms (Werner, Folsom, Mancl, & Syapin, 2001). Cortically generated electrophysiological components in response to gaps between 4000-Hz Gaussian-enveloped tone-pip markers also reveal similar gap detection thresholds of less than 4 ms in infants and adults (Trainor, Samuel, Desjardins, & Sonnadara, 2001).

On the other hand, using gaps in continuous noise, Werner, Marean, Halpin, Spetner, and Gillenwater (1992) found that 3-, 6-, and 12-month-old infants' gap thresholds (about 50 ms) were an order of magnitude greater than those of adults (about 5 ms). Even when differences in threshold criterion (d' of 0.5 for Trehub et al., 1995, and 70% or $d' > 1.0$ for Werner et al., 1992) are taken into account, gap threshold estimates differ substantially between these studies. One potential explanation of the difference is that the short tone-pip stimuli of Trehub et al. introduced slight spectral differences between the gap and no-gap stimuli that infants were able to perceive and use for detection, whereas any such cues were masked in the noise stimuli of Werner et al. However, this explanation seems unlikely given that there is no evidence that even adults can use these small spectral cues (Schneider et al., 1994). An alternative explanation is that the infant auditory system may be characterized by excessive adaptation, and that the use of continuous noise markers may underestimate infants' gap detection thresholds (Harris & Dallos, 1979; Westerman & Smith, 1984). Specifically, the onset after the gap may not be encoded reliably if the system is in a refractory state. While adaptation has not been studied directly, Werner (1999) did examine forward masking in infants. She found increased forward masking in 6-month-olds only at short time intervals between the signal and masker.

However, the relation between forward masking and adaptation is not clear; indeed, the locus of forward masking effects in the auditory system is not known.

In any case, all within-channel gap detection tasks, when used as indices of temporal resolution, share the problem that the limiting factor may be intensity coding rather than temporal coding per se. The present study examines between-channel gap detection for which the effects of intensity are minimized. Between-channel gap detection is also of interest because it bears a strong relation to language processing. In speech, the primary distinction between voiced and voiceless stop consonants (e.g., *b* and *p*) is the introduction of a short delay in the voice onset time (VOT). These VOT delays are essentially gaps in the sound that must be detected to correctly identify the consonant. Young infants are able to categorize speech sounds along the VOT continuum into voiced and voiceless categories, and over the following few months they will learn the particular categories that matter in the language to which they are exposed (Werker & Tees, 1984). Phillips (1999) has argued that between-channel gap detection tasks may provide a better model of VOT perception than within-channel tasks because the sounds before and after the delay are spectrally dissimilar and activate different perceptual channels. For this reason, between-channel gap detection in infancy may prove to be a stronger predictor of later language and reading problems than within-channel gap detection. However, any attempt to relate developmental deficits in between-channel gap detection to language outcome depends first on the delineation of the development of normal between-channel processing during infancy and early childhood, which is the primary goal of the present study.

To obtain a measure of the between-channel temporal resolution of the infant auditory system, it is crucial to consider possible confounding factors that can affect threshold measurements. First, it is important to obtain a bias-free measure. For example, although Davis and McCroskey (1980) found a steady decrease in within-channel gap thresholds between 3 and 11 years of age, their use of the method of limits (a paradigm in which gap duration is gradually increased over successive trials until the listener indicates that the gap was detected) raises the possibility that their observed age-related changes in performance might reflect changes in response bias over childhood.

Second, to avoid any potential contribution of adaptation differences between infants and adults, short markers can be used. Ecologically, the speech signals that infants must decode change rapidly over time, so the adaptation differences between infants and adults likely have little effect on speech sound perception.

Third, infants and young children are much worse than adults at detecting signals in noise (Bargones & Werner, 1994; Schneider, Trehub, Morrongiello, & Thorpe, 1989; Werner & Bargones, 1991). One major reason for presenting signals in noise is that the noise serves to mask the spectral splatter introduced by the abrupt onsets and offsets of signals. However, the use of noise can lead to underestimating infants' temporal resolution. Indeed, when signals are presented in noise, within-channel temporal resolution thresholds do not reach adult levels until 10 or 11 years of age. Irwin, Ball, Kay, Stillman, and Rosser (1985) showed that gap detection thresholds in broadband noise, and in narrowband noise presented against a background of broadband masking noise, decrease after 6 years of age, reaching adult levels at around 11 years. Prolonged developmental trajectories are also observed using temporal modulation transfer functions, which characterize the listener's ability to detect sinusoidal amplitude modulation of noise as a function of the frequency of modulation (Hall & Grose, 1994). Using a modified masking period paradigm, which compares listeners' tone-detection thresholds in modulated and unmodulated noise, Grose, Hall, and Gibbs (1993) found that children's thresholds reach adult levels between 6 and 10 years of age, depending on the frequency of the tones. Although detecting signals in noise is important for language learning in everyday environments, developmental differences in temporal resolution per se would be best addressed by presenting sounds in quiet.

Clearly, thresholds obtained in gap detection studies are influenced by a number of factors other than temporal resolution. In order to minimize potential effects of intensity coding, adaptation, and noise, the present study examines between-channel gap detection by presenting, in quiet, short tone-pip markers similar to those used in studies of within-channel gap detection (Schneider et al., 1994; Trehub et al., 1995).

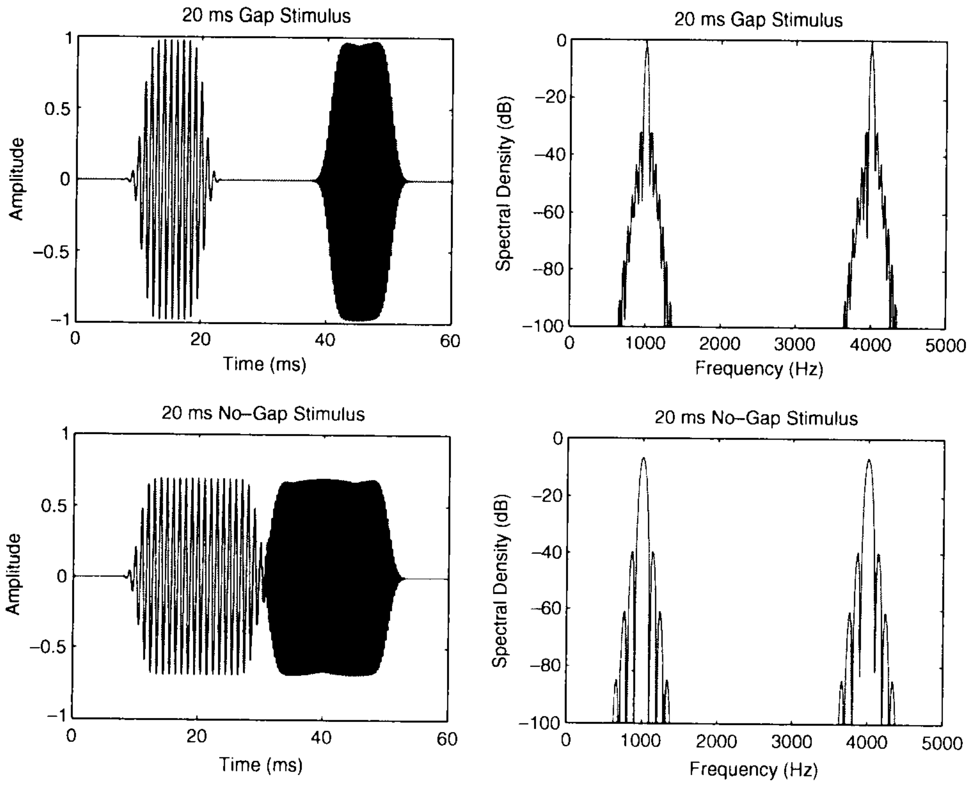
Method

Participants

Twenty-four infants between 6 and 7.5 months of age were tested. Infants were assigned to one of three experimental groups that differed in the tested gap durations. Each group (n = 8 per group) was tested with 50-ms gaps in the first block of test trials and 20-, 30-, or 40-ms gaps in the second block: 50-20, 50-30, or 50-40. Thirty other infants were tested, but their data are not reported here because they either failed to meet the training criterion described below or the testing had to be concluded prematurely due to crying and fussiness.

Thirty adult listeners (mean age = 20.7 years, SD = 2.02) were recruited from the psychology undergraduate participant pool at McMaster University and participated in exchange for course credit. Adult listeners were

Figure 1. A 20-ms gap stimulus (top row) and no-gap stimulus (bottom row) pair, shown in the temporal (left column) and spectral domains (right column). Each stimulus pair was equated for total power and duration.



assigned to one of three experimental groups: 50-10, 50-20, or 50-30 (each $n = 10$). They were all tested with 50-ms gaps in the first test block, followed by 10-, 20-, or 30-ms gaps in the second block. All adult listeners met the training criterion described below and completed all test blocks.

Stimuli

Two kinds of stimuli were created: gap and no gap (see Figure 1). Each consisted of two markers, a 1-kHz tone pip followed by a 4-kHz tone pip, chosen because in adults, absolute thresholds and equal loudness contours shift dramatically for tones below 500 Hz and above 5 kHz (Robinson & Dadson, 1956). A number of studies have examined audibility curves in infancy (Berg & Smith, 1983; Nozza & Wilson, 1984; Sinnott, Pisoni, & Aslin, 1983; Trehub, Schneider, & Endman, 1980). Overall, infants' thresholds are typically higher than those of adults, but these age-related differences tend to be greater for frequencies under 1 kHz (Olsho, Koch, Carter, Halpin, & Spetner, 1988). Unfortunately, there are no data from infants on the growth of loudness or equal loudness contours above threshold, so it is not possible to determine the relative loudness of 1 and 4 kHz tone pips for infants. However, we have no reason to believe that infants and adults differ dramatically in this regard for suprathreshold sounds; in any case, the markers are sufficiently separated in frequency that masking should not be a factor.

To minimize spectral splatter (introduction of frequencies not contained within the tones themselves) created by the abrupt onset and offset of the tones, each tone pip was temporally enveloped by a series of 10 overlapping Gaussian windows (see Schneider et al., 1994). Each window had a standard deviation of 1 ms, and the temporal offsets between peaks of successive windows was 1 ms. Consequently, each marker had a duration of roughly 10 ms. The use of Gaussian windows was modeled after within-channel gap stimuli created by Schneider et al., who demonstrated that Gaussian envelopes minimize spectral differences between gap and no-gap stimuli, thereby ensuring that listeners' discrimination of gap and no-gap stimuli reflected sensitivity to temporal differences between the sounds. Furthermore, Schneider et al. ruled out the possible use of spectral cues in gap judgments in a pilot study in which they progressively lowered the intensity of the stimuli, bringing increasingly more of the remote frequency regions containing spectral splatter under the threshold of audibility.

Gap size was defined in terms of the number of 1-ms Gaussian windows between the last window of the first marker and the first window of the second marker. Gap stimuli with gaps of various durations were created (10, 20, 30, 40, 50, and 70 ms). Matching no-gap stimuli were created for each gap size and contained imperceptible 2-ms gaps in order to avoid interaction between the 1-kHz and 4-kHz tones. Figure 1 shows 20-ms gap and no-gap stimuli. In order to ensure that listeners discriminated between the stimuli on the basis of the presence or absence of a gap, the leading and trailing markers within each gap and no-gap stimulus were equated for total power, and then each pair of gap and no-gap stimuli was equated for total power and duration. All stimulus creation and calibration was done in MATLAB. Stimuli were generated and presented at a sampling frequency of 44.1 kHz using custom written software running on a PowerMac G4 computer, amplified using a NAD C 352 amplifier and Grason–Stadler audiometric loudspeakers. To check the validity of our stimuli, we recorded the output from the loudspeaker using a Neumann KM 131 reference microphone, connected to a Tascam US-122 audio interface, and analyzed the recorded sound using FFT. The results showed no significant distortion.

Apparatus and Procedure

A conditioned head-turn procedure was used in which infants were reinforced for head turns in response to the occasional occurrence of a gap stimulus in a series of repeating background matched no-gap stimuli (stimulus onset asynchrony = 1 s). Infants were tested individually, seated on their parents' laps facing the experimenter in a single-walled sound-attenuated booth. Both the parent and the experimenter wore headphones that presented masking music to ensure that both the parent and the experimenter were unaware of experimental condition and trial type. A loudspeaker and a cabinet containing mechanical toys behind a sheet of smoked Plexiglas were located approximately 90° to the left of the infant. The illumination and activation of these toys were controlled by a computer outside of the booth, and served to reinforce infant listeners for head turns in response to the occasional gap stimuli. The experimenter communicated with the computer, signaling when the infant was ready for a trial, and when the infant made a head turn, through a custom-interfaced button box.

The no-gap stimulus repeated throughout the study. Two types of trials—gap or no gap—were initiated through a button push signal to the computer once the experimenter judged that the infant was looking straight ahead toward the experimenter (i.e., centered). On gap trials, a single gap stimulus replaced one no-gap stimulus within the series of background no-gap stimuli. The experimenter used a second button to signal infant head turns to the left toward the speaker and reinforcing toys. Infants were reinforced, by the activation and illumination of the toy, for head turns of at least 45° to the left that occurred within 2 s of the occurrence of the gap stimulus. On no-gap trials, the series of background no-gap stimuli continued unchanged. Infant head turns within 2 s of the beginning of the no-gap trials were recorded, but were not reinforced. In signal-detection terms, head turns during gap and no-gap trials therefore reflected hits and false alarms, respectively.

The experimental session consisted of a block of training trials followed by two blocks of test trials. During training, 70-ms gap stimuli were used because pilot studies had shown that the infants easily discriminated them from the matching no-gap stimuli. At the beginning of the block of training trials, the experimenter provided the infants with demonstration trials in which the toys were illuminated and activated automatically following the presentation of a gap stimulus. These demonstrations were meant to illustrate the contingency between the change in the background stimulus series and the toy. To test whether infants had indeed learned this contingency, demonstration trials were followed by training trials, which always contained a gap stimulus, and in which the toy only appeared if the infant turned toward the toy cabinet within 2 s of the gap stimulus. The training block consisted of up to 20 training trials interspersed with occasional demonstration trials. Infants were considered to have passed training and proceeded to the test trials after responding correctly on 4 consecutive training trials. In order to speed up the training process, the training block did not include control trials in which responses to a no-gap stimulus were assessed. However, infants were expected to be able to detect the 50-ms gaps in the subsequent block, which did include control trials, so this block served as a confirmation that infants understood the procedure.

Infants who passed training performed two blocks of 20 test trials. For all infants, the first block of trials tested detection of 50-ms gaps. The second block of trials tested gaps of 20, 30, or 40 ms, depending on the infants' group assignment (i.e., 50-20, 50-30, or 50-40). There was an equal probability of a gap or no-gap stimulus on any given test trial. No probe trials (change trials with a very easy discrimination, sometimes included to test for infant attention) were included in order to avoid effects of criterion shifts within trial blocks (Warren, 1985). For adult listeners, the procedure was identical except that rather than asking adults to respond with a head turn, they simply responded by raising their hand whenever they detected a gap stimulus.

Results

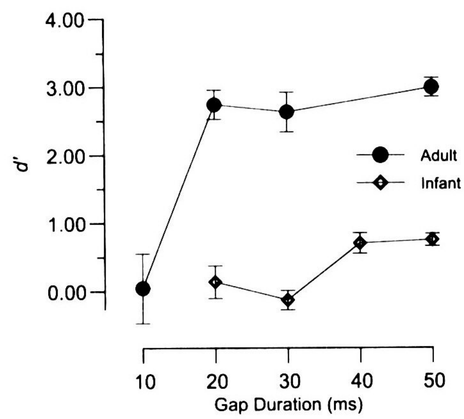
Individual *d′* values were calculated for each listener and gap size using hit and false-alarm rates that reflect the percentage of gap and no-gap trials on which the infant turned. However, due to the small number of trials, hit and false-alarm rates of zero did occasionally occur. In order to avoid infinite *d′*, modified hit and false-alarm rates were calculated by adding 0.5 to the number of hits and false alarms and by adding 1 to the total number of trials. This method modifies all *d′* values slightly, but preserves the relative order differences among values (Thorpe, Trehub, Morrongiello, & Bull, 1988). Using *d′* as a measure has a number of advantages, including that it is relatively unaffected by differences in response bias that might exist across subjects and across gap sizes. Individual *d′* values for each infant and adult listener for each gap size tested are shown in Table 1.

All infants performed a block of 50-ms gap trials, followed by a block of 20-, 30-, or 40-ms trials. A one-way analysis of variance (ANOVA) examined differences in performance in the second test block in which infants heard 20-, 30-, or 40-ms gap stimuli. As expected, performance varied as a function of gap size, $F(1, 21) = 4.38$, $MSE = 0.34$, $p < .05$. To examine the nature of this effect more closely, a series of one-sample *t* tests examined whether the mean *d′* values for each gap size were significantly greater than zero. As shown in Figure 2, significant detection was found for gap sizes of 50 ms, $t(23) = 8.10$, $p < .001$, and 40 ms, $t(7) = 4.66$, $p < .002$. However, *d′* values did not significantly differ from zero for gap sizes of 20 ms, $t(7) = 0.33$, *ns*, or 30 ms, $t(7) = -0.94$, *ns*. Looking across individual infants, *d′* values were only consistently positive for gap sizes of 50 and 40 ms. As can be seen in Figure 2, performance did not differ between gaps of 40 and 50 ms, suggesting that asymptotic performance of $d' = 0.74$ was reached by 40 ms. In order to compare performance on this between-channel task with that on the within-channel task of Trehub et al. (1995), we used their threshold criterion of $d' = 0.5$. While this criterion value is lower than typically used with adults, Trehub et al. provide a simple model that demonstrates that the effects of potential infant inattention on threshold are reduced when a lower criterion value is chosen. With a criterion of $d' = 0.5$, infants' between-channel gap threshold was 38 ms, compared with the value of 11 ms reported by Trehub et al. for within-channel gap detection. Note that these thresholds need to be considered estimates as the linear interpolation method used to compute the threshold is sensitive to the gap durations chosen in the experiment. However, the proportion of individual infants with above-threshold performance supports the estimated thresholds: 2 of 8, 0 of 8, and 6 of 8 infants within each gap condition had *d′* scores greater than 0.5 with 20-, 30-, and 40-ms gaps. respectively.

Table 1. Individual estimates of *d′* for infant and adult listeners.

		6 months		Adults	
Condition		Block 1	Block 2	Block 1	Block 2
50-40		1.37	0.78		
		0.93	0.72		
		1.21	0.24		
		0.16	0.09		
		0.19	0.67		
		0.72	0.94		
		0.52	1.48		
		0.87	0.67		
	M	0.75	0.70		
	SD	0.44	0.75		
50-30				3.38	3.36
				3.38	2.44
		−0.02	−0.07	2.46	3.38
		0.47	−0.35	1.22	0.83
		1.33	0.46	3.38	3.36
		0.49	−0.57	3.38	2.77
		1.83	0.23	2.80	3.38
		0.70	−0.02	0.18	1.20
		0.40	−0.02	2.19	2.79
		1.22	−0.70	3.38	2.79
	M	0.80	−0.13	2.57	2.63
	SD	0.60	0.75	1.11	0.92
50-20				3.38	3.38
				3.38	2.80
		0.07	0.48	3.38	2.46
		1.10	−1.22	3.38	2.44
		0.98	−0.94	3.38	3.38
		0.92	0.40	3.38	2.74
		0.97	0.23	3.36	3.38
		0.49	0.70	3.38	3.38
		1.22	1.22	3.38	2.12
		0.42	−0.09	3.38	1.33
	M	0.77	0.10	3.38	2.74
	SD	0.40	0.75	0.01	0.68
50-10				2.80	0.00
				3.36	1.06
				2.74	0.09
				3.38	0.59
				3.38	0.09
				3.38	−0.40
				3.36	−0.09
				2.79	0.09
				2.77	−0.18
				2.16	−0.80
	M			3.01	0.05
	SD			0.42	0.51

Figure 2. Mean *d′* values for infant and adult listeners as a function of gap size. Error bars represent the standard error of the mean.



A parallel analysis was performed on adult *d′* values. A one-way ANOVA examining differences in detection between groups that were tested on 10, 20, and 30 ms gaps in the second block found highly significant differences, $F(2, 27) = 44.56$, $MSE = 0.52$, $p < .001$. Next, a series of one-sample *t* tests examined whether the mean *d′* values differed significantly from zero. As shown in Figure 2, significant differences were found for 50-ms, $t(29) = 22.11$, $p < .001$, 30-ms, $t(9) = 9.06$, $p < .001$, and 20-ms gap sizes, $t(9) = 12.69$, $p < .001$. However, detection was not significantly different from zero for 10-ms gaps, $t(9) = 0.28$, *ns*. Looking across individual adult listeners, *d′* values were only consistently positive for gap sizes greater than 10 ms. This sudden drop in performance between 20 and 10 ms suggests that, as a group, adults' gap detection threshold lies between 10 and 20 ms. With the $d' = 0.5$ criterion used with infants, adult threshold was 12 ms. The proportion of individual adults with above-threshold performance supports this: 2 of 8, 8 of 8, and 8 of 8 adults within each gap condition had *d′* scores greater than 0.5 with 10-, 20-, and 30-ms gaps, respectively.

When infant and adult performance was compared, a number of differences were apparent. First, overall performance was worse in infants, such that their *d′* values for larger and more easily detected gap sizes asymptoted around 0.74, whereas adult *d′* values asymptoted at 2.79. Although infants' asymptotic performance was somewhat lower than that found for other perceptual tasks (e.g., tests of absolute detection; Trehub et al., 1980), this result mirrors those obtained by Trehub et al. (1995) in their comparison of within-channel gap detection thresholds in infants, children, and adults. Trehub et al. (1995) argued that these age-related differences likely reflect lapses of attention in infants and are presumably independent of sensitivity to different gap sizes. Furthermore, Trehub et al. (1995) provided a simple model of the effects of inattention on *d′* and suggested that differences between groups in attention are minimized with a low criterion such as $d' = 0.5$.

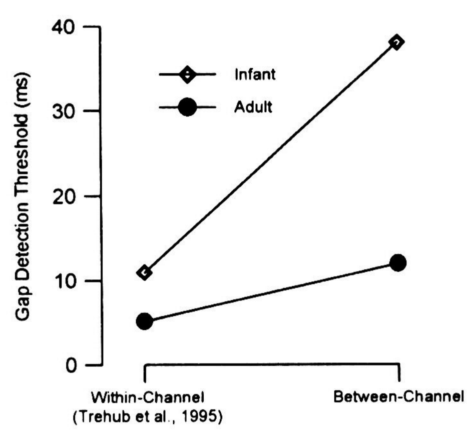
Beyond the difference in the level of asymptotic performance, which likely has little relation to temporal resolution per se, age-related differences were found in the smallest reliably detected gap. Under conditions in which adults' thresholds were 12 ms, infants' thresholds were about 38 ms.

Discussion

Many studies show that adults have better between-channel than within-channel gap detection thresholds (Fitzgibbons et al., 1974; Formby, Gerber, et al., 1998; Formby, Sherlock, et al., 1998; Grose et al., 2001; Phillips et al., 1997; Taylor et al., 1999). We have shown the same dichotomy in infants: Between-channel thresholds in 6-month-olds were much higher than within-channel thresholds reported by Trehub et al. (1995) using similar stimuli and methodology. Most interesting is the finding that between-channel gap detection appears to be less mature at 6 months than within-channel detection. As shown in Figure 3, infant within-channel thresholds were about 6 ms greater than adult within-channel thresholds (data reported by Trehub et al.), whereas infant between-channel thresholds were 26 ms greater than adult thresholds, suggesting a more protracted developmental trajectory for the maturation of between-channel temporal mechanisms. Given that within-channel gap thresholds may be measuring efficiency of intensity coding rather than temporal coding per se, the present findings are particularly important in demonstrating immaturity in temporal processing mechanisms in infancy.

Any strict comparison of between- and within-channel gap detection is limited by a number of issues,

Figure 3. Estimated gap detection thresholds for within-channel (Trehub et al., 1995) and between-channel (present study) stimuli for infant and adult listeners.



most of which center around the essential requirement that the between-channel stimuli make use of markers with two different frequencies, which cannot both be equated with the single marker frequency used in a within-channel task. For example, temporal resolution is better at higher frequencies in adults (Shailer & Moore, 1983, 1985), though more recent work suggests that these effects may only apply to nondeterministic stimuli such as bandpass noise (Moore, Peters, & Glasberg, 1993). Furthermore, there is some evidence that children's temporal resolution reaches adult levels earlier at higher frequencies (Irwin et al., 1985). Although the exact nature of integration across frequency channels with different temporal resolutions is still unexplored, between-channel resolution could be expected to be as poor as temporal resolution in the worst of the two relevant channels. Because our lowest frequency was higher than that used by Trehub et al. (1995), if anything, we are likely underestimating the difference between infants' within- and between-channel thresholds.

Another potential complication introduced by different frequency markers in between-channel tasks are developmental differences in the perceived intensity of different frequencies. While infants' sensory detection thresholds are closer to adult levels at 4000 Hz than at 1000 Hz, there are no studies on the growth of loudness perception, nor are there studies measuring equal-loudness contours above threshold in infants. However, even if infants perceive the 1000-Hz tone as somewhat less loud than the 4000-Hz tone in comparison to adults, it is unlikely that this had much influence on the results. Studies indicating deterioration in performance with intensity difference across the markers used spectrally identical markers (Plomp, 1964). Furthermore, when the markers are spectrally far apart, the onset of the trailing marker is always heard as an event (cf. Oxenham, 2000), making it unlikely that small or moderate differences in intensity between markers would contribute substantially to increased difficulty in gap detection.

Related to the issue of differential frequency sensitivity is the potential use of slight spectral differences to distinguish gap and no-gap stimuli (see Figure 1). Although steps were taken to minimize these differences (see Method section), they do provide a possible nontemporal means of detecting gap stimuli. However, such cues do not affect adults' within-channel thresholds (Schneider et al., 1994). Given that infants are less sensitive than adults to intensity differences (Schneider, Bull, & Trehub, 1988; Sinnott & Aslin, 1985), it is unlikely that infants made use of these small spectral cues.

Implications

The marked immaturity of between-channel gap thresholds in infancy likely reflects a progression from peripheral to central maturation in the auditory system, and suggests that between-channel mechanisms are relatively central. Although at birth the peripheral auditory pathway appears to function at adult levels (Eggermont, Brown, Ponton, & Kimberley, 1996; Ponton, Eggermont, Coupland, & Winkelaar, 1992), the central auditory system exhibits a much more prolonged developmental trajectory, with cortical adultlike activity as measured by electroencephalography appearing only during adolescence (Ponton, Eggermont, Kwong, & Don, 2000; Shahin, Roberts, & Trainor, 2004).

The functional significance of between-channel temporal resolution is also important. Phillips (1999) argued that between-channel gap detection tasks are likely more related than within-channel tasks to the discriminations required for speech perception because the spectral content of speech varies rapidly. Thus, between-channel gap thresholds in individual infants may serve as a diagnostic tool to help identify infants at risk for language problems. The reliance of between-channel gap detection on more central processes, as well as its similarity to processes necessary for VOT perception, suggests that between-channel gap detection thresholds may provide an even stronger predictor of later language outcome than previous studies of within-channel gap detection (Trehub & Henderson, 1996).

The use of between-channel gap detection thresholds as a potential predictor of later language ability depends a great deal on methodological advancements in infant testing. With the method of constant stimuli used in the present study, infants can only be kept in a testable state for the completion of at most two conditioned head-turn procedures, resulting in performance measures for only two gap sizes, making a threshold difficult to determine in an individual infant. Adaptive procedures have also been developed and successfully implemented to test absolute thresholds in infants (e.g., Berg & Smith, 1983; Olsho et al., 1988; Sinnott & Aslin, 1985; Trehub, Bull, Schneider, & Morrongiello, 1986). However, the clinical application of adaptive procedures to test gap detection thresholds may prove challenging, as reliable data may not be obtained from a substantial number of infants. This may depend a great deal on the nature of the perceptual task involved. Whereas yield rates (i.e., the percentage of infants for whom thresholds can be obtained) can be relatively high for tests of absolute thresholds for the detection of a stimulus, they appear to be lower for the estimation of discrimination thresholds (or thresholds for the detection of features within a stimulus). For example, in Werner et al.'s (1992) study of gap detection, threshold measures were only obtained in 9 out of 17 three-month-olds, 12 out of 19 six-month-olds, and 6 out of 14 twelve-month-olds, despite the fact that if testing was not successful one day, it was repeated on a subsequent day. Thus, although between-channel gap detection holds promise as a diagnostic indicator of risk for language impairment, such a test will depend on the development of methods for obtaining reliable thresholds in most individual infants.

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Contact author: Laurel J. Trainor, Department of Psychology, Neuroscience and Behaviour, McMaster University, Hamilton, Ontario L8S 4K1, Canada. E-mail: ljt@mcmaster.ca