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Research Article

Gap Detection in School-Age Children and Adults: Center Frequency and Ramp Duration

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Purpose: The age at which gap detection becomes adultlike differs, depending on the stimulus characteristics. The present study evaluated whether the developmental trajectory differs as a function of stimulus frequency region or duration of the onset and offset ramps bounding the gap.
Method: Thresholds were obtained for wideband noise (500–4500 Hz) with 4- or 40-ms raised-cosine ramps and for a 25-Hz-wide low-fluctuation narrowband noise centered on either 500 or 5000 Hz with 40-ms ramps. Stimuli were played continuously at 70 dB SPL, and the task was to indicate which of 3 intervals contained a gap. Listeners were 5.2- to 15.1-year-old children (*n* = 40) and adults (*n* = 10) with normal hearing.
Results: Regardless of listener age, gap detection thresholds for the wideband noise tended to be lower when gaps were shaped using 4-ms rather than 40-ms ramps. Thresholds also tended to be lower for the low-fluctuation narrowband noise centered on 5000 Hz than 500 Hz. Performance reached adult levels after 11 years of age for all 4 stimuli. Maturation was not uniform across individuals, however; a subset of young children performed like adults, including some 5-year-olds.
Conclusion: For these stimuli, the developmental trajectory was similar regardless of narrowband noise center frequency or wideband noise onset and offset ramp duration.

Gap detection quantifies a listener's ability to detect a brief temporal separation between two marker stimuli or an interval of silence embedded in an ongoing stimulus. Sensitivity to the presence of a gap is thought to be important for processing natural stimuli. For example, gap detection between markers that are separated in frequency has been argued to rely on the same cues as discriminating speech sounds that differ with respect to voice onset time (e.g., /ba/ and /pa/; Elangovan & Stuart, 2008). Although gap detection is widely used as a measure of temporal resolution, thresholds of adult listeners depend on the spectral and temporal characteristics of the stimuli bounding the gap (e.g., Eddins, Hall, & Grose, 1992; Grose, Buss, & Hall, 2008). A recent study by Buss, Hall, Porter, and Grose (2014) argued that the development of adultlike gap detection may, likewise, depend critically on spectral and temporal features of the stimulus. The ability to detect a gap in a spectrally wide stimulus was argued to mature earlier in childhood than the ability to detect a gap in low-fluctuation narrowband noise. The present study evaluated whether the time course of development differs depending on the stimulus frequency region or the duration of onset and offset ramps used to shape the gap. One motivation for evaluating these stimulus features is that signal detection in quiet matures later in childhood for brief low-frequency stimuli than for high-frequency or long-duration stimuli (He, Buss, & Hall, 2010; Trehub, Schneider, Morrongiello, & Thorpe, 1988). Another motivation for evaluating frequency and ramp duration is that effects related to these features have bearing on the interpretation of gap detection data reported by Buss et al. (2014).

Buss et al. (2014) evaluated gap detection in school-age children and adults for a band of Gaussian noise that was either 25 or 1000 Hz wide. In two additional conditions, a 25-Hz-wide band of noise was modified to either minimize or accentuate envelope modulation; these noises were described as low-fluctuation and staccato noise, respectively. The 1000-Hz-wide stimulus was gated on and off by using 4-ms ramps, and the 25-Hz-wide stimuli were gated by using 40-ms ramps. The rationale for using longer

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ramps for the narrow bandwidth stimuli was to make the ramps perceptually similar to the band's inherent modulation. There were three main findings in that study. First, thresholds for the 25-Hz-wide bands depended on envelope fluctuation. Listeners of all ages tended to have lower thresholds for stimuli with less fluctuation (low fluctuation < Gaussian < staccato noise). This result was described in terms of the perceptual similarity between features of inherent envelope fluctuation and an added gap. The more pronounced the fluctuation, the more it interfered with performance, an effect previously observed for adults (Grose et al., 2008; Munkner, Kohlrausch, & Puschel, 1996). Second, thresholds for the 1000-Hz-wide band of Gaussian noise tended to be lower than those for the 25-Hz-wide band of Gaussian noise regardless of listener age. In isolation, this result could be due to reduced effective modulation of the wide band, resulting from a combination of increased inherent modulation rate and limited temporal resolution for envelope fluctuation (Viemeister, 1979), or the presence of cues across multiple auditory filters (Eddins et al., 1992; Grose, 1991). Third, although gap detection thresholds were comparable for adults in the 25-Hz-wide low-fluctuation noise and the 1000-Hz-wide Gaussian noise conditions, children's thresholds converged on those of adults at different ages in these conditions (12.1 and 7.2 years, respectively). One explanation for this result is that children learn to use the across-channel cues that benefit gap detection for wideband stimuli before they learn to use high-quality within-channel cues.

Although Buss et al. (2014) argued that the distribution of cues across frequency was likely to be the critical factor in maturational differences for the 25-Hz-wide low-fluctuation and 1000-Hz-wide Gaussian conditions, there were other stimulus differences that could have affected results. One difference was the frequency range over which cues were available. Although both the 25-Hz-wide and the 1000-Hz-wide bands were centered on 2000 Hz, listeners could have based their responses for the wider stimulus on auditory filter outputs above or below the filter centered on 2000 Hz. Another factor to consider is differences in the ramp duration: 40 ms for the 25-Hz-wide low-fluctuation condition and 4 ms for the 1000-Hz-wide Gaussian condition. If the developmental time course differs as a function of frequency region or ramp duration, then interpretation of the results of Buss et al. (2014) in terms of across-frequency processes would be undermined.

Effect of Stimulus Frequency on Gap Detection

The role of stimulus frequency for gap detection in adults appears to be highly dependent on the other stimulus features, with some data indicating that frequency plays a dominant role and others indicating that it plays no role in performance. Fitzgibbons (1983) measured gap detection thresholds for low-pass and high-pass noise stimuli, with cutoff frequencies of 500 to 5660 Hz. Increasing the low-pass cutoff improved performance by about 2 ms/oct, but changes in the high-pass cutoff had little or no effect. In contrast, Eddins et al. (1992) measured gap detection thresholds for noise bandwidths ranging from 50 to 1600 Hz, with upper frequency cutoffs ranging from 660 to 4400 Hz. Thresholds improved with increasing bandwidth, but there was no effect of frequency region in that data set. Snell, Ison, and Frisina (1994) hypothesized that frequency effects play a dominant role in gap detection when the stimulus bandwidth is at least 50% of the highest frequency, but that bandwidth plays an important role below that point. That study further observed a nonlinear effect of frequency when the bandwidth was fixed at 1000 Hz. Thresholds fell with increasing stimulus frequency up to 4000 Hz and then rose with further increases in frequency, a result that could indicate a *sweet spot* in frequency for gap detection. This nonlinear effect of stimulus frequency contrasts with the results of Hall, Grose, and Joy (1996), where thresholds for 20-Hz-wide bands of noise were approximately constant across a range of 250 to 8000 Hz. One possible explanation for the different effects of stimulus frequency with 1000- and 20-Hz bands of noise is that inherent fluctuation poses a larger impediment to performance with the 20-Hz-wide band, obscuring effects related to center frequency.

Two studies pertinent to the effect of frequency on gap detection in children covaried stimulus frequency and bandwidth. Wightman, Allen, Dolan, Kistler, and Jamieson (1989) measured gap detection thresholds in 3- to 7-year-olds using half-octave noise bands centered at either 400 or 2000 Hz. Gap detection thresholds were higher at 400 Hz than 2000 Hz, but adultlike gap detection thresholds were observed by approximately 6 years of age, regardless of the center frequency of the noise. Irwin, Ball, Kay, Stillman, and Rosser (1985) measured gap detection in 6- to 12-year-olds and adults by using octave-wide bands of noise centered at 500, 1000, or 2000 Hz. Gap detection thresholds in that study improved with increasing frequency for all age groups. In contrast to the results of Wightman et al. (1989), young children had higher thresholds than adults for noise bands centered at 500 Hz but not 1000 and 2000 Hz. Differences in bandwidth notwithstanding, this result would be consistent with the earlier maturation at high than low frequencies, a trend sometimes observed in other psychoacoustic paradigms. For example, Olsho (1984) argued that frequency discrimination in infants matures earlier at high than at low frequencies (e.g., 4000 Hz vs. 500 Hz). In a similar way, signal detection thresholds in quiet appear to mature earlier at high than at low frequencies (Olsho, Koch, Carter, Halpin, & Spetner, 1988; Trehub et al., 1988), an effect that extends into early childhood when the signal to be detected is brief (He et al., 2010). On the basis of these observations, the tentative hypothesis of the present study is that children may achieve adultlike gap detection earlier in development for narrow bands of low-fluctuation noise at high than at low frequencies.

Effect of Ramp Duration on Gap Detection

The duration of onset and offset ramps used to shape a gap could reasonably be expected to affect the precision with which that gap is detected in both adults and children. This expectation is based on the observation that shorter ramps could provide more precise and salient indicators of an added gap. Physiological data in mice indicate that using a short ramp to shape marker onset at the end of the gap could be particularly beneficial for the neural encoding of that gap (Barsz, Benson, & Walton, 1998), a finding that was corroborated with behavioral data in mice (Ison, Castro, Allen, Virag, & Walton, 2002). Allen, Virag, and Ison (2002) tested whether a similar effect of ramp duration could be observed in behavioral data from human adults. They found that apart from effects on overall gap duration, there was no evidence that the postgap onset ramp duration was of particular importance for detection. Gap thresholds were approximately equivalent for ramps with durations up to 8 ms, provided that gap duration was measured from the 4-dB down point. The conclusion that gap detection thresholds are insensitive to ramp duration is corroborated by supplemental data from Eddins et al. (1992), showing that one highly trained adult's gap thresholds for a bandpass filtered noise were similar for ramp durations of 1 to 17 ms. One caveat is that these two studies evaluated ramp durations that were more than a factor of two shorter than the 40-ms ramp duration used by Buss et al. (2014).

There are no data directly pertinent to the effect of ramp duration for gap detection in school-age children. One possibility is that children's reduced sensitivity to changes in intensity (e.g., Buss, Hall, & Grose, 2013) would impair their ability to detect a gap bounded by relatively long onset and offset ramps when compared with adults. Whereas Allen et al. (2002) reported that adults used intensity decrements of approximately 4 dB in a broadband noise stimulus to detect the presence of a gap, school-age children may require an even greater level change to detect a gap (>4 dB). This larger intensity decrement criterion would necessarily result in higher gap detection thresholds, with a larger child–adult difference for gaps bounded by longer-duration ramps.

In summary, the present study was designed to evaluate the developmental trajectory for gap detection as a function of band center frequency and onset and offset ramp duration. The specific frequencies (500 and 5000 Hz) and ramp durations (40 and 4 ms) were chosen to clarify the role of these factors in the results reported by Buss et al. (2014).

Methods

Listeners

Participants included 10 adults and 40 children with normal hearing sensitivity, defined as pure-tone thresholds equal to or better than 20 dB HL at octave frequencies between 250 and 8000 Hz (American National Standards Institute, 2010). Adults ranged in age from 19.8 to 32.7 years (M = 23.5 years). Children ranged in age from 5.2 to 15.1 years (M = 8.7 years). Child ages were approximately uniformly distributed on the logarithm of age, with fewer older than younger children due to the expectation of decelerating maturation. One child (9.6 years) was enrolled in the study and later excluded due to strong evidence of flagging attention; thresholds in one condition progressively rose (worsened) by a factor of 10 across replicate threshold estimates. Four children (5.8, 6.8, 7.4, and 15.1 years) had previously participated in the gap detection study of Buss et al. (2014). For these children, a minimum of 4 months elapsed between data collection for the two experiments.

Stimuli

The stimuli used to investigate possible effects of center frequency on gap detection were low-fluctuation 25-Hz-wide bands of noise centered at either 500 or 5000 Hz. For these narrowband stimuli, the ramps used to introduce temporal gaps were 40-ms raised cosines. As in Buss et al. (2014), low-fluctuation noise was generated using an iterative process. Beginning with a band of Gaussian noise, the time waveform was divided by its Hilbert envelope, transformed into the frequency domain, restricted to its original bandwidth, and transformed into the time domain. This process was repeated eight times. An example of the resulting stimulus envelope is illustrated in Buss et al. (2014, Figure 1). The potential impact of ramp duration on gap detection for wideband stimuli was investigated by using 4500-Hz-wide Gaussian noise (500–5000 Hz), with 4-ms or 40-ms raised cosines used to introduce temporal gaps.

All stimuli were generated with a 12207-Hz sampling rate. Noise samples were 10.7 s (2^{17} points) long. These samples were played continuously at 70 dB SPL, without discontinuities apart from imposed gaps. A new sample of noise was generated prior to each threshold estimation track. Gap duration was defined as the interval between the beginning of the stimulus offset and the beginning of the subsequent onset. When the gap duration was less than the ramp duration, the offset and onset overlapped such that the stimulus amplitude in the center of the gap did not fall to zero.

Procedures

Threshold estimation procedures were controlled using a custom MATLAB script, which generated noise stimuli and loaded them into a real-time processor (RP2, TDT, Alachua, FL). Stimuli were routed from the real-time processor to a headphone buffer (HB7, TDT) and presented to the listener's left ear using a circumaural headset (HD 265, Sennheiser, Wedemark, Germany). Data were collected in a double-walled sound-attenuating booth. All listeners were paid an hourly rate for participation.

Stimulus intervals were 500 ms in duration, with 500-ms interstimulus intervals. Each interval was indicated visually on a touch-sensitive computer monitor, and listeners indicated their responses by touching the screen or using a mouse. A jigsaw puzzle animation was revealed over the course of a threshold estimation track, with one piece revealed following each correct response. Progress for each track was indicated with a progress bar at the top of the screen, showing the proportion of track reversals obtained. At the completion of a track, the remaining puzzle pieces were removed, revealing a complete cartoon, which performed a 2-s animation.

Thresholds were measured by using a three-alternative forced-choice procedure that incorporated a two-down, one-up stepping rule to estimate the gap duration associated with 71% being correct. At the beginning of a track, gap duration was varied by a factor of 1.41. This step size was reduced to a factor of 1.19 following the second track reversal. The track was terminated after eight reversals, and the threshold estimate for a track was the geometric mean of the final six reversals. At least three threshold estimates were collected in each condition. A fourth was collected if the first three differed by more than a factor of 1.5. The geometric mean of all threshold estimates obtained was taken as the final estimate of threshold for each condition. Conditions were presented in random order, with all tracks for a particular condition completed before moving on to the next condition. The maximum allowable gap duration was 500 ms, but all tracks stayed below this limit.

Data Analyses

Statistical analyses were performed on the logarithm of gap duration. The logarithm of age was also used in the following analyses, based on the expectation that development is more rapid for younger than older children. For some analyses, child data were divided into four groups according to age: 5.0 to 6.5 years, >6.5 to 8.5 years, >8.5 to 11.0 years, and >11.0 to 15.1 years. These divisions resulted in approximately equal-sized groups. Group thresholds were computed as the geometric means of individuals' thresholds. Data distributions were evaluated and nonparametric statistics used when indicated. In particular, Spearman rank order correlations were used to evaluate associations between threshold and child age, due to the finding of larger individual differences in younger listeners. A one-tailed significance criterion was adopted to evaluate the effects of listener age on the basis of the prior prediction of poorer performance in younger listeners.

Results

Figure 1 shows gap detection thresholds for individual child listeners (circles) as a function of age. The mean adult threshold is indicated with an asterisk, and dotted lines indicate the 95% confidence interval around that mean. Results for each of the four stimulus conditions are shown in separate panels: low-fluctuation narrowband stimuli centered at 500 Hz (upper left panel) and 5000 Hz (upper right panel), and wideband stimuli with 40-ms ramps (lower left panel) and 4-ms ramps (lower right panel). In all four conditions, gap detection thresholds tend to decrease with increasing child age. Spearman correlations were computed to evaluate the association between child age and gap detection threshold. For low-fluctuation narrowband stimuli, correlations were $r_S = -.34$ ($p = .016$) and $r_S = -.43$ ($p = .003$) for 500- and 5000-Hz center frequencies, respectively. For the wideband stimuli, correlations were $r_S = -.50$ ($p = .001$) and $r_S = -.42$ ($p = .003$) for 40- and 4-ms ramps, respectively.

In addition to effects related to child age, inspection of the individual data in Figure 1 reveals that some of the youngest children consistently performed at or near the range of adults' thresholds, whereas others performed substantially more poorly. The best performers in each age group were identified by determining the rank order of thresholds and averaging the rank across all four conditions; listeners falling in the bottom third of this distribution are indicated with symbol shading in Figure 1. The four listeners who had previously participated in a gap detection experiment all performed better than the 50th percentile for their respective age groups, but only one of them (6.8 years) met the criterion for best performers. As indicated in the figure, individuals who performed well in one condition were highly likely to perform well in the other conditions. For all child listeners, thresholds were highly correlated across the four conditions, with values ranging from $r_S = .73$ to $r_S = .82$ ($p < .001$). The magnitude of these correlations is high compared with correlations with child age ($r_S = -.34$ to $-.50$), consistent with the observation that the marked individual differences cannot be attributed entirely to listener age.

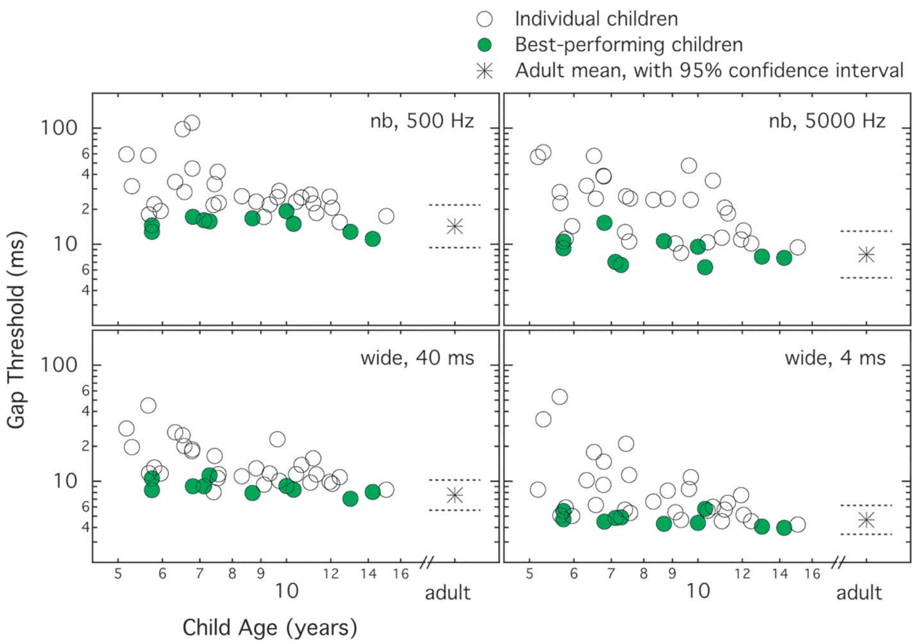
A possible explanation for poor performance in some children is variable attention to the task, which might be reflected in higher variability across track reversals. Indeed, children with higher thresholds did seem to respond less consistently. This was quantified by computing the correlation between thresholds and the standard deviation across all track reversals contributing to the final threshold estimate in each condition.[1] Evaluating just the data of child listeners, the results ranged from $r_S = .48$ ($p = .001$; low-fluctuation noise at 500 Hz) to $r_S = .63$ ($p < .001$; low-fluctuation noise at 5000 Hz). For all four conditions, the geometric standard deviation of reversals was a stronger predictor of thresholds than child age, although not significantly so ($p \geq 0.226$ two tailed[2]).

Figure 2 shows the geometric mean of gap detection thresholds for listeners in each age group. Symbol shape reflects the stimulus condition, as defined in the legend. As in Figure 1, a general improvement in thresholds with increasing age is evident. Although thresholds differed in the four conditions, the general improvement with age appears to be largely parallel. In the narrowband conditions, thresholds were a factor of ~1.6 higher at 500 Hz than 5000 Hz for all groups, and in the wideband conditions thresholds were a factor of ~1.9 higher for the 40-ms than

[1]As for the other statistics, the log of gap duration (in milliseconds) at each track reversal was used for computing the standard deviation of reversals.

[2]The equivalence of Spearman correlations was evaluated by using a Fisher transformation, as described by Myers and Sirois (2006).

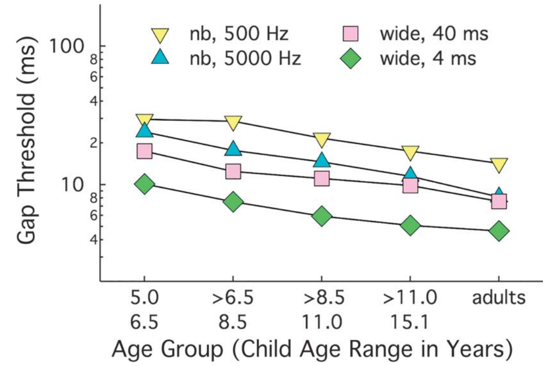
Figure 1. Gap detection thresholds are shown as a function of age for individual children (circles). The geometric mean of adult gap detection thresholds (asterisks) is shown at the right of each panel, with dotted lines indicating the 95% confidence interval around adult means. Results include low-fluctuation narrowband (nb) noise centered at 500 Hz (upper left panel) or 5000 Hz (upper right panel) and wideband (wide) noise with 40-ms ramps (lower left panel) or 4-ms ramps (lower right panel). Filled symbols indicate individual children whose mean threshold rank across conditions fell in the bottom third for their age group; this group of good performers consists of the same individuals across all four panels.



the 4-ms ramps. Although heteroscedasticity of the data limits the options for statistical analysis of the thresholds, the variance across groups was nearly uniform when the ratio of thresholds was examined.[3] The ratio of thresholds (in milliseconds) was, therefore, evaluated by using univariate analysis of variance. For the ratio of thresholds in the 500- and 5000-Hz conditions, the effect of age group was nonsignificant, $F(4, 45) = 0.89$, $p = .480$, $\eta_p^2 = .073$. Likewise, for the ratio of thresholds in the 40- and 4-ms ramp conditions, the effect of age group was also nonsignificant, $F(4, 45) = 0.55$, $p = .704$, $\eta_p^2 = .046$. If age affected thresholds differently at different frequencies or for different ramp durations, an effect of group would be expected. The absence of an effect of group in these analyses is consistent with the idea that development is similar for the two center frequencies and for the two ramp durations. There was, however, evidence of development in both data sets for all groups of children. This was evaluated by performing a series of *t* tests with unequal variance. The geometric mean of thresholds in the 500- and 5000-Hz conditions was significantly lower for adults than any of the child age groups, including the children >11.0 to 15.1 years ($p = .026$). Likewise, the geometric mean of thresholds in the 40- and 4-ms conditions was significantly lower for adults than any child age group, including the children >11.0 to 15.1 years ($p = .034$).

One reason for the overall poorer gap detection of younger listeners could be reduced sensitivity to changes in intensity. That is, younger listeners may require a larger

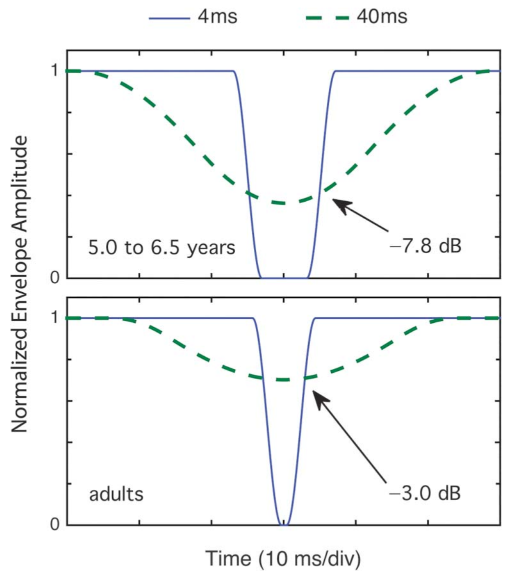
Figure 2. Group geometric mean gap detection thresholds are shown for five age groups: 5.0 to 6.5 years, >6.5 to 8.5 years, >8.5 to 11.0 years, >11.0 to 15.1 years, and adults. Symbol shape reflects the stimulus condition: low-fluctuation narrowband (nb) noise centered at 500 Hz (downward triangles) or 5000 Hz (upward triangles) and wideband (wide) noise with 40-ms ramps (squares) or 4-ms ramps (diamonds).



[3]The ratio between thresholds resulted in more nearly uniform variance across groups because of the strong correlation between thresholds in different conditions. That is, taking the ratio of thresholds factored out consistent individual differences.

criterion change in level at the beginning and end of the gap. Comparing thresholds in the 4- and 40-ms ramp conditions could provide an estimate of that level criterion, assuming other aspects of the task are the same for the two ramp durations. In particular, if age effects are due solely to differing sensitivities to changes in level, and sensitivity to gap duration is constant across ramp duration conditions, then the criterion can be estimated by (a) plotting the envelopes associated with threshold duration gaps in the two conditions, with the center of each gap aligned in time, and (b) determining the level at which the two envelopes intersect. This approach is illustrated in Figure 3, which shows idealized stimulus envelopes associated with gaps at the group mean threshold for 5.0- to 6.5-year-olds (top panel) and adults (bottom panel). Recall that gap duration was originally defined as the interval between the beginning of the offset and subsequent onset; when the gap duration exceeds the ramp duration, this is equivalent to measuring gap duration from the 6-dB down points of the offset and onset ramps. For 5.0- to 6.5-year-olds, mean thresholds using the original definition were 10.1 ms for the 4-ms ramp condition (solid line) and 17.5 ms for the 40-ms ramp condition (dashed line). If gap durations were measured instead from the 7.8-dB down points, then the gap detection threshold would be 9.6 ms in both conditions. For adults, mean thresholds using the original definition were 4.6 ms for the 4-ms ramp condition (solid line) and 7.6 ms for the 40-ms ramp condition (dashed line). Measuring gap duration at the 3.0-dB down points on the offset and onset ramps results in a threshold of 5.8 ms in both conditions.

Figure 3. Idealized envelopes are shown for threshold duration gaps with either 4-ms ramps (solid lines) or 40-ms ramps (dashed lines), positioned on the abscissa such that the midpoints of each gap are aligned in time. Tick marks on the abscissa indicate 10 ms per division. The top panel shows mean gap durations for the youngest group of children (5.0 to 6.5 years), and the bottom panel shows means gap durations for adults. The level at which the envelopes cross, the criterion level change, is indicated in each panel.



An analysis of individual listener's thresholds was carried out to evaluate the extent to which differences in the level-change criteria could account for the age effects illustrated in Figures 1 and 2. As expected, there was a trend for larger criterion level changes in younger listeners, although the association between criterion and child age failed to reach significance (r_S = .24, p = .072 one tailed). The gap duration defined by each child's criterion differed significantly as a function of child age, with younger children obtaining larger criterion-adjusted gap thresholds than older children (r_S = −.38, p = .008 one tailed). These results provide tentative support for the idea that the development of intensity discrimination may play a role in the accuracy with which the beginning and end of a gap are represented in the central auditory system, but that this factor does not fully account for the age effect observed in gap detection. The significant negative correlation between age and criterion-adjusted gap duration is evidence that there are additional factors related to the minimum duration below criterion that underlie detection of a gap.

Discussion

This study was designed to evaluate the effects of stimulus frequency and ramp duration on children's gap detection thresholds. Mean thresholds improved with child age in all conditions, a trend consistent with the previous results of Buss et al. (2014) and Wightman et al. (1989), and with the 500-Hz data of Irwin et al. (1985). This pattern of development was not significantly different for narrowband stimuli at 500 versus 5000 Hz, or for wideband stimuli shaped with 4- versus 40-ms ramps. In all four stimulus conditions, thresholds were significantly higher for children than adults, even for the oldest age group tested (>11.0 to 15.1 years).

Effect of Stimulus Frequency on Gap Detection

In the present study, gap detection thresholds were lower for the low-fluctuation narrowband noise at 5000 Hz than 500 Hz, a difference that was approximately a factor of 1.6 for all five age groups. This result contrasts with published data on gap detection with narrowband Gaussian noise in adults (Eddins et al., 1992; Hall et al., 1996). For example, Hall et al. (1996) reported that thresholds for 20-Hz-wide bands of noise were constant for center frequencies from 250 to 8000 Hz. There are at least two plausible explanations for this discrepancy between data sets. The first has to do with the greater inherent fluctuation in Gaussian noise than in low-fluctuation noise. We know that inherent noise fluctuation can elevate gap detection thresholds in both children and adults (Buss et al., 2014; Grose et al., 2008). It is possible that previous data on gap detection for Gaussian noise bands at different center frequencies were limited by inherent fluctuation, obscuring an effect of frequency. This possibility is undermined somewhat by the results of Moore, Peters, and Glasberg (1993), who reported pure-tone gap detection as a function of frequency (100–2000 Hz). In that study, thresholds were approximately U shaped, with the lowest thresholds at 800–1000 Hz. Most relevant to the present data set, thresholds for a presentation level of 70 dB SPL were comparable at 400 and 2000 Hz. Extrapolating from these data, pure-tone gap thresholds at 5000 Hz could be higher—not lower—than those at 500 Hz.

The second factor that may play a role in the frequency effect observed with low-fluctuation narrowband noise has to do with the degree to which the stimulus retains its low-fluctuation characteristics after passing through an auditory filter. The reduced envelope fluctuation of a low-fluctuation noise depends critically on preservation of magnitude and phase characteristics. The relatively wide auditory filter at 5000 Hz may preserve these characteristics better than the narrower filter at 500 Hz. Hall, Buss, Ozmeral, and Grose (2016) recently provided some evidence that auditory filtering affects the internal representation of low-fluctuation noise, albeit for bandwidths wider than 25 Hz. That study also reported that adults' thresholds were consistently approximately 20 ms for 25-Hz-wide bands of low-fluctuation noise centered on 500, 1000, 2000, or 4000 Hz. One difference between the stimuli used by Hall et al. (2016) and those of the present study is that stimuli in the previous study were gated on during each listening interval rather than playing continuously, as in the present study. Continuous presentation has been observed to cause loudness adaptation, particularly at high stimulus frequencies (Hellman, Miskiewicz, & Scharf, 1997; Miskiewicz, Scharf, Hellman, & Meiselman, 1993). Although it is possible that the greater loudness adaptation at high frequencies could play a role in lower thresholds for a continuous noise at 5000 Hz than at 500 Hz, it is not clear that adaptation differs significantly between these frequency regions for a presentation level of 70 dB SPL (Hellman et al., 1997; Tang, Liu, & Zeng, 2006).

Whereas gap detection depended on the stimulus frequency in the present study, the pattern of thresholds as a function of listener age did not. The improvement in performance with listener age was parallel for low-fluctuation noise centered on 500 and 5000 Hz. These results contrast somewhat from those of Irwin et al. (1985), who reported an age effect for gap detection in octave-wide bands of Gaussian noise at 500 Hz but not at 1000 or 2000 Hz. The absence of a frequency effect for 25-Hz-wide bands in the current paradigm implicates bandwidth differences in the effects reported by Irwin et al. (1985). That possibility is broadly consistent with the data of Buss et al. (2014), with the caveat that the very narrow (25-Hz) bandwidth and the use of low-fluctuation noise represents a very different stimulus than that used by other researchers.

Effect of Ramp Duration on Gap Detection

In the present study, gap detection thresholds for wideband noise were lower for 4-ms than 40-ms ramps, an effect that was approximately a factor of 1.9 for all five age groups. Recall that gap durations were defined as the delay between the initiation of marker offset at the beginning of the gap and the initiation of marker onset at the end of the gap. For gaps that are at least as long as the ramp duration, this is equivalent to measuring gap duration from the 6-dB down (half-rise) point. We know that young children are less sensitive to dynamic changes in stimulus intensity compared with older children and adults (Buss et al., 2013; Hall & Grose, 1994), so it is possible that younger listeners may require larger changes in level before they can detect a gap. The criterion level change required to detect a gap was estimated by assuming that thresholds for the 4- and 40-ms ramp conditions were consistent within an individual. These criterion values were modestly correlated with child age, although that association failed to reach significance. The criterion-adjusted gap thresholds, on the other hand, were significantly correlated with child age. These results suggest that that development of the ability to detect a change in stimulus level (i.e., the criterion change) does not fully account for the age effects observed when thresholds were defined as the delay between initiation of offset and subsequent onset.

Individual Differences Across Conditions

Despite the clear trend for lower thresholds with increasing child age, there were some children even in the youngest age group who performed similarly to adults. These individual differences were strongly correlated across conditions, such that good performance in one condition was a strong predictor of good performance in other conditions. There was also a strong correlation between variance in track reversals and threshold. This is consistent with the possibility that the poorer child performers varied over time in their ability to selectively attend to the optimal stimulus cue. This variability could take the form of occasional lapses in attention, but it could also represent instability in the stimulus cue used to select the *different* interval. The stimuli in the present experiment were based on random noise samples, so the sounds presented in each interval were likely to differ on a number of dimensions in addition to the presence or absence of a gap. A listener who is not as skilled at selectively attending to cues associated with a gap may respond to one of those nonpredictive features. For example, a poorer performer may tend to select the interval associated with greater inherent envelope modulation, particularly when the gap is relatively short and the associated cue is very subtle.

There is some precedence in the psychoacoustic literature for consistently adultlike performance in a subset of young children. For example, Moore, Ferguson, Halliday, and Riley (2008) measured pure-tone frequency discrimination thresholds in 6- to 11-year-olds and adults. They found a trend for lower thresholds in older children, with median performance improving from approximately 10% (6–7 years) to 1.5% (adults). Despite this marked improvement in median thresholds, 24% of 6- to 7-year-olds had thresholds within the 95% confidence interval of adult thresholds. That is, some of the youngest children achieved adultlike performance. A parallel training study conducted by Halliday, Taylor, Edmondson-Jones, and Moore (2008) showed that performance was predicted by age, nonverbal IQ, and the probability of lapses in attention, indicating that good frequency discrimination thresholds relied on higher-level cognitive abilities. Similar cognitive factors could have affected performance in the present study.

Comparisons With Buss et al. (2014)

Buss et al. (2014) reported that children achieved adultlike gap detection thresholds earlier in development for wideband Gaussian noise than for narrowband low-fluctuation noise. This was interpreted as showing that the ability to integrate cues across frequency (in the wideband stimulus) developed earlier than the ability to make use of fine temporal cues at a single frequency (in the low-fluctuation narrowband noise). One potential weakness of this interpretation was the fact that gap detection was examined at only one center frequency (2000 Hz), such that the wideband stimulus provided cues at lower and higher frequencies than the narrowband stimulus. As reported here, there was no group-by-frequency interaction for low-fluctuation narrowband noise centered at 500 or 5000 Hz. As such, it seems unlikely that the developmental effects observed by Buss et al. (2014) were related to the availability of cues at different frequencies. Likewise, there was no evidence in the present data set for different developmental trends with 4-ms and 40-ms ramp durations. This result makes it unlikely that differing ramp duration for the wideband and narrowband stimuli influenced the age at which adultlike thresholds were observed by Buss et al. (2014).

The age associated with mature gap detection for narrowband low-fluctuation noise in the present data set was consistent with that observed by Buss et al. (2014), with mature performance after 11 years of age in both cases. However, these two data sets differ in the age at which children's thresholds converged on those of adults for the wideband stimulus. In the previous study, children's thresholds were adultlike by approximately 7 years of age for the wideband (1500–2500 Hz) stimulus. In the present study, thresholds for the wideband (500–5000 Hz) stimulus remained elevated relative to adults' even in the oldest group of children (>11.0 to 15.1 years) for both ramp durations. It is unclear how to account for the differences across studies in the development of gap detection with wideband stimuli, but one possibility is that gap detection for the 1000- and 4500-Hz-wide bands of Gaussian noise are differentially affected by external stimulus variability and internal limits. These internal limits are sometimes described as internal noise or listener efficiency.

Internal and external sources of error in a psychoacoustic task combine, with the larger of the two sources of noise dominating performance (Jesteadt, Nizami, & Schairer, 2003), such that marked stimulus variability tends to mask individual differences in listeners' internal noise. Buss et al. (2014) argued that the pronounced envelope fluctuation of narrowband staccato and Gaussian noise stimuli masked age differences in internal noise, whereas the reduced stimulus fluctuation associated with low-fluctuation noise bands allowed those age-related differences in internal noise to affect thresholds. In the case of gap detection for wideband noise, the provision of additional channels of information provided by increasing bandwidth from 1000 to 4500 Hz could reduce the effects of stimulus variability by introducing additional opportunities for spectral integration. This possibility is broadly consistent with the finding that adults' mean thresholds were higher for the 1000-Hz-wide Gaussian noise (10.9 ms; Buss et al., 2014) than for the 4500-Hz-wide Gaussian noise (4.6 ms; present data set, 4-ms ramps). Reduced effects of stimulus variability with increasing noise bandwidth could unmask effects related to internal noise in younger listeners.[4] If this is the case, then the Buss et al. (2014) finding of adultlike performance at different ages for low-fluctuation narrowband noise and 1000-Hz-wide Gaussian noise could have more to do with the balance between internal and external limits to performance than reliance on cues in one versus multiple auditory channels.

Another difference between the present data and those of Buss et al. (2014) is the finding of adultlike performance for some children as young as 5 years of age in the present study, whereas young children's thresholds were more consistently elevated relative to those of adults in the previous study. For the 500-Hz low-fluctuation noise condition in the present study, thresholds for the best-performing third of 5.0- to 6.5-year-olds were only a factor of 1.1 greater than those of adults. In contrast, the best-performing third of 5.0- to 6.5-year-olds in the earlier study had low-fluctuation noise thresholds that were a factor of 2.2 greater than those of adults. A similar pattern of results is evident for the wideband stimulus with 4-ms ramps; thresholds for the best-performing 5.0- to 6.5-year-olds were a factor of 1.1 higher than those of adults in the present data set and a factor of 1.4 in the earlier data set. Apart from stimuli, the present and previous studies were largely the same: the same experimenters collected data using the same protocol and user interface. Given the numbers of children in each group, the best-performing third of listeners represents only three or four individuals. Although it is possible that stimulus differences resulted in more adultlike performance for the

[4]The proposal here is that earlier adultlike performance for the 1000-Hz-wide than for the 4500-Hz-wide band is due to relatively greater effects of stimulus variability for the 1000-Hz-wide stimulus. By this logic, an even narrower band should be associated with more stimulus variability and therefore even earlier adultlike performance. However, this prediction is inconsistent with the finding of more protracted development for the 25-Hz-wide Gaussian noise stimulus than for the 1000-Hz wide stimulus in the data of Buss et al. (2014). One consideration in evaluating this result is that envelope fluctuation at the output of a single auditory filter is very different for a 25- and 1000-Hz-wide stimulus, so it is unclear whether to attribute performance differences to within-channel cues or the ability to combine cues across auditory filters.

best-performing children in the present study, it is also possible that this difference is due to chance.

Summary

Results of the present study support the following conclusions:

1. Gap detection for a 25-Hz-wide band of low-fluctuation noise is better for a center frequency of 5000 Hz than 500 Hz. Thresholds improve with listener age, but the effect of frequency is consistent across listener age groups.
2. Gap detection for a 4500-Hz-wide band of Gaussian noise (500–5000 Hz) is better for a ramp duration of 4 ms than of 40 ms. Thresholds improve with listener age, but the effect of ramp duration is consistent across listener age groups. Age effects were not fully captured by using a simple model of reduced sensitivity to changes in stimulus intensity.
3. Age effects in the group data were observed past 11 years of age in all four stimulus conditions. However, some individual children's thresholds were consistently adultlike even for the youngest age group (5.0- to 6.5-year-olds).

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