Monaural temporal integration and temporally selective listening in children and adults

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This study used two paradigms to investigate the development of temporal integration and temporally selective listening. Experiment 1 measured detection as a function of duration for a pure tone at 1625 or 6500 Hz. At both frequencies thresholds of children younger than 7 years old were higher than those for older children and adults. The pattern of temporal integration was similar across groups for the 6500-Hz signal, but younger children showed relatively more temporal integration for the 1625-Hz signal due to high thresholds for the briefest 1625-Hz signal. Experiment 2 measured detection thresholds for one or for three brief tone pips presented in a noise masker. In one set of conditions, the noise masker consisted of 100-ms steady bursts interleaved with 10-ms temporal gaps. In other conditions, the level of the central 50 ms of the 100-ms masking noise bursts was adjusted by either +6 or −6 dB. Children showed higher thresholds but similar temporal integration compared with adults. Overall, these data suggest that children are less efficient than adults in weighting the output of the monaural temporal window at 1625 but not 6500 Hz. Children are efficient in combining energy from brief temporal epochs that are separated by noise. © *2010 Acoustical Society of America.* [DOI: 10.1121/1.3397464]

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I. INTRODUCTION

Previous studies have indicated that monaural temporal processing is often poorer in children than adults, whether measured by gap detection (Irwin *et al.*, 1985; Wightman *et al.*, 1989; Trehub *et al.*, 1995), the detection of a long-duration signal in a band-limited modulated noise (Grose *et al.*, 1993), modulation detection (Hall and Grose, 1994), or the detection of a brief signal in a forward or backward masking paradigm (e.g., Buss *et al.*, 1999; Hartley *et al.*, 2000). The underlying mechanisms for differences in temporal processing ability between adults and children are controversial. One possibility is that poorer temporal performance of children is due to a longer monaural temporal window, the time interval over which the integration of auditory information is compulsory. However, the results of some studies have suggested that the reduced fidelity of temporal processing in children may instead be accounted for by poor processing efficiency (e.g., Hall and Grose, 1994; Hartley and Moore, 2002; Hill *et al.*, 2004). The notion of reduced efficiency of processing in children is that even though age has little effect on the peripheral encoding of sound, central factors related to the processing of peripheral information may be less effective in children than in adults. This processing efficiency account emphasizes constraints of the central nervous system rather than the peripheral auditory system. Although the concept of listening efficiency could provide reasonable explanations for the poor temporal processing ability in children, it has significant limitations since the *nature* of such inefficiency is unclear.

The temporal processing has been described with a model that includes four stages: a bank of bandpass filters representing the frequency selectivity of the peripheral auditory system, a compressive non-linear device that follows each of these filters, a sliding temporal integrator (temporal window), and a decision device (e.g., Viemeister and Wakefield, 1991; Moore *et al.*, 1988; Plack and Moore, 1990). It has been proposed that adults can optimize temporal processing performance by applying decision weights that emphasize the output of the temporal window during temporal epochs associated with the best signal-to-noise ratio (SNR) (Moore *et al.*, 1988; Breebaart, *et al.*, 2002). In contrast, children might show a reduced ability to optimize the temporal weighting compared with adults, which could be the *nature* of poor temporal efficiency in children.

Results of a recent study reported by Hall *et al.* (2007) suggested that children did differ from adults in the ability to optimize temporal weighting in the analysis of brief binaural cues (i.e., temporally selective listening). That study used two paradigms based on the masking level difference (MLD) (Hirsh, 1948). The first was modeled closely on a method developed by Kollmeier and Gilkey (1990) to characterize the temporal epoch during which the auditory system integrates binaural difference cues (the binaural temporal window). That study examined the ability to detect a brief Sπ signal as a function of its temporal placement with respect to an abrupt interaural phase transition in the masking noise (No to Nπ or Nπ to No). Adult data in this and related paradigms (e.g., Grantham and Wightman, 1978, 1979) have indicated that the binaural temporal window is substantially longer than the monaural temporal window. The results of Hall *et al.* (2007) were consistent with an interpretation that the binaural temporal window shape and duration were simi-

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lar for children and adults, but that children based their performance on a non-optimal weighting of the temporal window output. Children appeared to apply the highest weights to the temporal window output during epochs that were delayed slightly relative to those of adults (i.e., children "listened late").

In the second MLD paradigm employed by Hall *et al.* (2007), the noise did not have an abrupt interaural phase transition, but instead was either No or Nπ throughout its duration. The signal (Sπ) was either brief (20 ms) or long (410 ms) in duration. The hypothesis was that if children indeed listened late with respect to the signal, this should result in a reduced MLD for the brief signal. This would occur because listening relatively late for the brief Sπ signal would substantially reduce the signal-to-noise ratio of the detection cue and therefore reduce the associated detection benefit. In contrast, the MLD for the long-duration signal should be relatively adult-like because a delay in temporal weighting of the binaural cues relative to signal onset would not substantially reduce the signal-to-noise ratio with which the long-duration Sπ signal was processed. The results of Hall *et al.* (2007) were consistent with this hypothesis, indicating that the MLDs of adults and children were not significantly different for the long-duration signal, but that the children had smaller MLDs than the adults for the brief signal (due to relatively high NoSπ thresholds).

Results of developmental studies indicate that there are some parallels between monaural and binaural temporal processing. For example, children have a reduced ability to make use of monaural acoustic cues coincident with envelope minima of an amplitude modulated narrow band noise (Grose *et al.*, 1993). Similarly, Hall *et al.* (2004) showed that children also had poorer performance in exploiting binaural information in the envelope minima of a narrow band noise. It is possible that the relatively poor performance of children in the monaural and binaural temporal paradigms reflects a common form of listening inefficiency rather than factors related to the time constants of the monaural or binaural temporal windows. A goal of the present study was to test the idea that the binaural results shown by Hall *et al.* (2007) may reflect a developmental effect that also applies to monaural hearing, wherein children are relatively poor at listening selectively in time. The possibility that children may listen relatively late with respect to the timing of the signal in monaural hearing is consistent with previously reported findings that although the improvement with age in both forward and backward masking appear to follow the same developmental course, children generally show more pronounced threshold elevations for backward than for forward masking when compared to adults (Buss *et al.*, 1999). By this account, the monaural temporal window would have same shape/duration in adults and children, but the ability to optimally weight the output of a sliding temporal window would be reduced in children.

The present study investigated development of the ability to listen selectively in time for the detection of brief monaural signals. It was hypothesized that children are poorer than adults in optimizing the temporal weighting of the output of the monaural temporal window with respect to the timing of the signal. The first experiment to test this hypothesis involved the detection of signals in low-level masking noise and was intended to assess whether children demonstrate a poor ability to listen in a temporally selective way even in a simple task that does not require the extraction of brief signals from temporally proximal bursts of masking noise (as in most temporal masking paradigms). This experiment used a straightforward temporal integration (Hughes, 1946; Plomp and Bouman, 1959) paradigm. If the hypothesis that children do not listen in a temporally selective manner is correct, then children should have a different pattern of short-term temporal integration as compared to adults for the detection of a brief signal. Note that in the binaural study of Hall *et al.* (2007) a 20-ms signal was considered brief because this duration is short with respect to the time constant of the binaural temporal window. The temporal window characterizing monaural performance is shorter than that characterizing binaural performance (e.g., Kollmeier and Gilkey, 1990). Therefore, the 20-ms signal might not be considered brief relative to the time constant of monaural temporal window. In adults the monaural temporal window is approximately 10 ms in duration, with estimates ranging from 3.2 to 26 ms (Moore *et al.*, 1988; Kollmeier and Gilkey, 1990; Holube *et al.*, 1998; Viemeister, 1977). For a signal that is relatively brief with respect to the presumed duration of the temporal window, even a relatively small error in the temporal weighting should have a negative consequence for detection, due to the fact that the error will reduce the SNR contributing to the decision. Thus, if children listen late, they would be expected to have particularly high thresholds for very brief signals. As the duration of the signal is extended to approach and exceed the time constant of the sliding temporal window, the negative consequences non-optimal weighting is expected to diminish/disappear, due to the fact that the signal-to-noise ratio will be high over an extended interval.

Previous research on the development of temporal integration is relatively sparse. Temporal integration results from 3 to 7 month old infants (Berg, 1991; Werner and Marean, 1991; Berg and Boswell, 1999) have generally been consistent with greater temporal integration than found for adults due to relatively poor infant thresholds for short-duration signals consisting of either clicks or 10–16 ms tone bursts. Interestingly, the report by Berg and Boswell (1999) indicated that infants' temporal integration was more adult-like at higher masker levels, and that the adult/infant difference in temporal integration was absent for a relatively high-frequency (4-kHz) signal. The finding of greater temporal integration in infants than adults in some conditions is generally in agreement with the hypothesis tested here.

Data on temporal integration in school-aged children have been somewhat inconsistent. Maxon and Hochberg (1982) concluded that temporal integration functions were significantly steeper for children than for adults. However, thresholds measured for signals at different frequencies were averaged together despite differences in hearing sensitivity as a function of frequency, making the results difficult to interpret. Furthermore, they found that the slope of the temporal integration function did not change in children across the age range tested (4–12 years), and the comparison to adults was based upon data from literature. In contrast to the interpretation of Maxon and Hochberg (1982), results reported in two other studies indicated that the temporal integration functions of normal-hearing children did not differ from those of adults (Barry and Larson, 1974; Olsen and Buckles, 1979). The conflicting conclusions about the development of temporal integration notwithstanding, none of these studies examined durations that were sufficiently brief to provide a satisfactory test of the hypothesis examined here.

The particular approach used here is similar to that of Oxenham *et al.* (1997), where a 6500-Hz signal that is brief with respect to the monaural temporal window can be used without resulting in substantial spectral splatter across frequency channels. In this paradigm, thresholds for a 6500-Hz signal are determined for a range of durations from 2 to 128 ms, measured from the half-rise point. The spectrum of the shortest (2-ms) signal is 500 Hz at the 6-dB down point. Therefore the stimulus falls primarily within the equivalent rectangular bandwidth (ERB) of the auditory filter at 6500 Hz (672 Hz; Glasberg and Moore, 1990). This stimulus configuration enables valid measurement of temporal integration since the auditory filter should not have a large effect on the temporal characteristics of the signal (Oxenham *et al.*, 1997). A particularly high threshold for briefest signals would be consistent with the hypothesis that children listen late. We also measured temporal integration for a 1625-Hz signal. Although introduction of spectral splatter precludes using signals briefer than about 8 ms at this frequency, the 1625-Hz signal frequency was included in order to determine whether temporal integration data trends were comparable across signal frequency.

The second experiment examined a potentially more challenging paradigm that required the extraction and temporal integration of multiple, brief signals from temporally proximal masker bursts. This experiment was based on a temporal integration paradigm developed by Viemeister and Wakefield (1991). In this adaptation of their paradigm, detection thresholds were determined for one or for three brief tone pips that were presented in the context of a continuously presented, amplitude modulated noise masker. In the simplest condition, the noise was steady except for the fact that it contained 10-ms temporal gaps separated by 100-ms masker epochs. Each 10-ms tone pip of the signal was temporally centered in a masker gap. When three tone pips were presented, they occurred in three consecutive gaps; the three pips were therefore separated in time by 100 ms. In some conditions the level of the masking noise between the 10-ms gaps was manipulated; in these cases the central 50 ms of the 100-ms noise separating the gaps was adjusted by either +6 or −6 dB. Viemeister and Wakefield (1991) noted that good performance in similar conditions depended upon very selective temporal listening and combination of cues over time, particularly under conditions where the intervening noise level was relatively high (e.g., +6 dB). They found that varying the masking noise level between signals did not have an effect on temporal integration in normal-hearing adults, consistent with an interpretation that such listeners can "intelligently" select and combine temporally distributed "multiple looks" in a near-optimal way. Whereas Viemeister and Wakefield (1991) used gated maskers, the present study used continuous maskers since results of one previous study indicate that gating *per se* can disrupt the temporal integration process (Bacon *et al.*, 2000).

In summary, the purpose of experiment 1 is to characterize the ability to listen in a temporally selective manner under conditions in which the masker is stationary, and the purpose of experiment 2 is to assess this ability under conditions of dynamic masker level where the listener must combine epochs of signal energy that are separated by intervening noise. Together these two paradigms should help characterize the abilities of children to listen in a temporally specific fashion.

II. EXPERIMENT 1

A. Methods

1. Listeners

Recruitment was carried out separately for the 6500-Hz and the 1625-Hz signal conditions. Children were recruited by flyers posted in the immediate medical/research community and in local schools. All of the children were in the age-appropriate grade in school. The adult listeners all responded to emails or flyers and were mainly university students and employees. For data collection at 6500 Hz, a group of 18 children ranging in age from 5.2 to 9.9 years (mean =7.4 years) was recruited, including nine females and eight children younger than 7.0 years. The associated adult group was composed of ten listeners, ranging in age from 20.8 to 53.5 years (mean=29.4 years), including nine females. For data collection at 1625 Hz, a group of 19 children ranging in age from 4.9 to 10.0 years (mean=7.2 years) was recruited, including ten females and ten children younger than 7.0 years. The associated adult group was composed of ten listeners, ranging in age from 18.7 to 45.6 years (mean =32.6 years), including eight females. Of the child listeners, 22 had previously participated in at least one hearing study and five completed both 6500- and 1625-Hz portions of the present study. Of the adult listeners, ten had previously participated in at least one hearing study and none completed both 6500- and 1625-Hz portions of the present study.

All listeners had normal-hearing sensitivity as defined by pure-tone detection thresholds of 20 dB hearing level (HL) or better at octave frequencies from 250 to 8000 Hz (ANSI, 2004). None of the listeners had a history of chronic ear disease or a history of speech, language, and learning disorders. All listeners were paid for participation.

2. Stimuli

The masker was a bandpass Gaussian noise presented at 20 dB/Hz and played continuously over the course of a threshold estimation track. Detection thresholds were measured for a range of signal durations. In the first set of conditions, the masker spanned 2000 to 12 000 Hz, and the signal was a 6500-Hz pure tone. Signal gating was controlled by 1-ms raised-cosine ramps, and signal duration was 2, 8, 32, or 128 ms. In a second set of conditions, the masker spanned 500–3000 Hz, and the signal was a 1625-Hz pure tone. In these conditions the signal was ramped on and off with 4-ms raised-cosine ramps, and signal duration was 8, 32, 128, or 512 ms. In all cases signal duration is reported based on the half-rise point of the ramping function.

The experiment was run using a custom MATLAB script and a real-time DSP (RP2, TDT) that controlled stimulus gating and signal presentation. Maskers were 2^{18}-point arrays that were computed in MATLAB and loaded into the circuit at the beginning of each track. These arrays were generated in the frequency domain, with Gaussian draws defining the real and imaginary components in the passband of the masker. When played continuously at a 48.8-kHz rate these stimuli looped seamlessly with a period of 5.4 s. From the output of the real-time processor, stimuli were routed through a headphone buffer and then presented monaurally to the left earphone of a Sennheiser HD 265 linear headset.

3. Procedures

Stimuli were presented in a three-alternative forced-choice procedure, with the listening interval defined as the longest signal duration associated with each signal frequency (512 ms at the low frequency and 128 ms at the high frequency). The inter-stimulus interval was 500 ms. One interval, chosen at random, contained the signal. Study participants were required to select the interval containing the signal. Thresholds were measured in a three-down one-up adaptive track, estimating the signal level associated with 79% correct (Levitt, 1971). At the outset of each track, signal level adjustment was made in steps of 4 dB; this step size was reduced to 2 dB after the second track reversal. A track continued until a total of eight reversals had been obtained. The final threshold was computed as the mean signal level at the last six track reversals. Threshold estimates were obtained blocked by condition, run in quasi-random order for each observer. Three threshold estimates were obtained in each condition, with a fourth estimate obtained in cases where the first three spanned a range of 3 dB or more. The mean and standard deviation of the three/four threshold estimates were recorded.

Listening intervals were indicated visually with computer graphics. After every correct response a computer animation simulated the placement of a jigsaw puzzle piece. A progress bar at the top of the screen tracked the number of reversals obtained up to that point. At the end of a threshold estimation run the puzzle was completed and the underlying image performed a brief animation. All listeners used this interface and completed one practice run before data collection began. Study participants were tested in a double-walled sound-attenuating booth. Adults completed all conditions in a single 1-h session. Child listeners typically took two sessions, but for two of the younger children a third session was required; in most cases these two or three sessions were scheduled within a two-week period. The five child listeners who provided data at both signal frequencies completed the 6500-Hz conditions first and the 1625-Hz conditions within six months following entry into the study. No consistent trends of improvement were noticed for any listeners during the course of data collection.

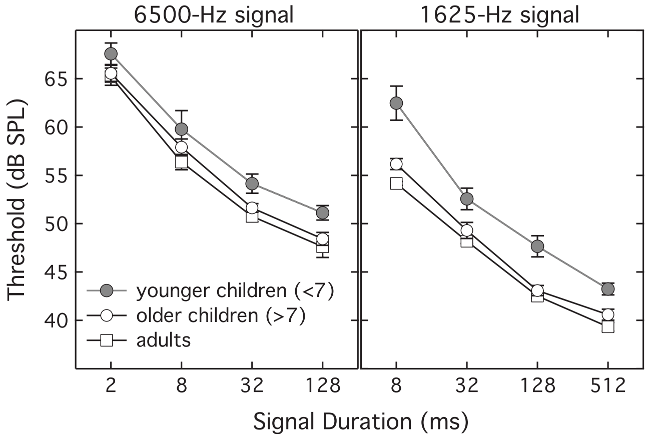

FIG. 1. Mean thresholds (dB SPL) measured at different durations, plotted separately for adults and children, as indicated in the legend. Error bars show ± one standard error. The filled circles show data of younger children, open circles show data for older children, and the open squares the data of adults. The left panel shows results at 6500 Hz, and the right panel shows results at 1625 Hz.

During performance of the task the child listeners were monitored carefully for signs of inattentiveness, and motivation was maintained by giving encouragement and breaks as necessary to maintain vigilance. In addition to the child listeners described above, two additional children began but did not complete the study. One was a 5-year-old who demonstrated over 20 dB test-retest variability and was excused from further testing. The other, age 6 years, did not wish to proceed with further testing after completing initial thresholds. These two children were not included in the description of listeners groups above.

B. Results and discussion

Figure 1 shows the mean signal detection thresholds plotted as a function of signal duration. Left and right panels in Fig. 1 show results for the 6500- and 1625-Hz signal, respectively. Symbols indicate data for three observer groups, including adults (open square symbols), children older than 7 years (open circles), and children younger than 7 years (filled circles). Despite differences in stimuli and experimental procedures, signal detection thresholds obtained from adult listeners at 6500 Hz are generally consistent with the data reported by Oxenham *et al.* (1997). In all three groups of listeners signal detection thresholds decreased with increasing signal duration up to the maximum duration tested. Consistent with previous studies with adults (Hughes, 1946; Garner and Miller, 1947; Plomp and Bouman, 1959; Florentine *et al.*, 1988; Oxenham *et al.*, 1997), our results showed that the signal detection thresholds decreased by approximately 3 dB per doubling in duration up to 32 ms at 6500 Hz and 128 ms at 1625 Hz, followed by a slower decrease in thresholds up to the maximum duration tested in the present study. In other words, thresholds improved approximately linearly as the duration was incrementally lengthened by a factor of 4. Similar to the results reported by Oxenham *et al.* (1997), the integration functions are steeper at shorter durations than at longer ones for all listener groups, a trend that is especially evident at 6500 Hz.

Comparing results shown in Fig. 1 across groups indicates that the data of older children closely resembled those of adults, but the data of the younger children reflect poorer sensitivity overall. Threshold functions for the 6500-Hz signal frequency are approximately parallel for the three groups, but those for the 1625-Hz signal frequency show a trend for greater threshold elevation at the briefest signal duration for the young child listeners. These group effects were evaluated with a pair of repeated-measures analyses of variance (ANOVAs), one analysis for each signal frequency. In both cases there were three levels of group (younger children, older children, and adults) and four levels of signal duration (2, 8, 32, and 128 ms for 6500 Hz; 8, 32, 128, and 512 ms for 1625 Hz).

For the 6500-Hz signal frequency there was a significant main effect of duration ($F_{3,75}=503.06$, $p<0.0001$) and a main effect of group ($F_{1,25}=4.71$, $p<0.05$), but there was no interaction between group and signal duration ($F_{6,75}=0.34$, $p=0.91$). A repeated contrast on the across-subjects factor of group revealed that the older children did not differ from the adults ($p=0.38$), but that the younger children performed significantly more poorly than older children (2.3 dB; $p<0.05$). Whereas children younger than 7 years of age performed more poorly than older children or adults, all groups benefited in a parallel fashion from increasing the signal duration. The lack of a significant interaction between group and duration indicates that temporal integration did not differ across groups. The mean difference in threshold between 2-ms and 128-ms signal was 17.6 dB for adults, 17.1 dB for older children, and 16.4 dB for younger children.

For the 1625-Hz signal frequency there was a significant main effect of signal duration ($F_{3,78}=515.57$, $p<0.001$), a main effect of group ($F_{2,26}=21.95$, $p<0.0001$), and an interaction between duration and group ($F_{6,78}=3.87$, $p<0.01$). A repeated contrast on the across-subjects factor of group revealed that the older children did not differ from the adults ($p=0.17$), but that the younger children performed significantly more poorly than older children (4.2 dB; $p<0.001$). The significant interaction reflects the fact that the younger children had particularly poor thresholds for the briefest stimulus duration (see Fig. 1). Because of the poor threshold for the briefest tone, the younger children had relatively large temporal integration, quantified as the difference between thresholds for the 8-ms condition and the 512-ms condition (19.2 dB). In contrast, temporal integration was 14.8 dB for adults and 15.6 dB for older children.

These analyses of group data suggest that most of the developmental effects occurred before 7 years of age. This finding was explored further by evaluating individual child listeners' thresholds as a continuous function of age. An advantage of this approach is that it allows an evaluation of developmental effects to be carried out without imposing a categorical age variable that might be considered to be somewhat arbitrary. Figure 2 shows thresholds for the shortest and longest signal duration, plotted as a function of child age, with mean adult data shown for comparison. Thresholds for the intermediate signal durations, omitted from this figure for visual clarity, are generally consistent with intermediate data patterns. The vertical lines in each panel indicate the 7-year category boundary between younger and older child groups. Consistent with the group analysis, reported above, Fig. 2 shows an improvement in thresholds as a function of age for both signal frequencies and signal durations. This improvement appears to be steepest for the briefest 1625-Hz signals.

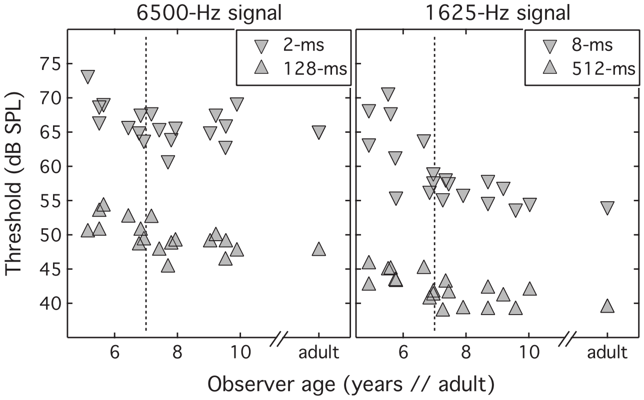

FIG. 2. Individual child thresholds in select conditions are plotted as a function of listener age, along with the associated mean adult threshold. Results for the 6500-Hz signal frequency are shown in the left panel, and those for the 1625-Hz signal are show in the right panel. As indicated in the legend associated with each panel, down-pointing triangles show thresholds for the shortest signal duration, and up-pointing triangles show those for the longest signal duration.

Statistical analyses were performed on the data from child listeners using age as a continuous variable and a general linear model design, with four levels of duration. For the 6500-Hz data there was a main effect of duration ($F_{3,48}=7.51$, $p<0.0001$) and a main effect of age ($F_{1,16}=5.99$, $p<0.05$), but no interaction ($F_{3,48}=0.23$, $p=0.87$). On average, thresholds as a function of age were fitted with a line having slope -0.84 dB/yr. As in the group analyses, these results provide no evidence of greater temporal integration for younger than older children. For the 1625-Hz data there was a significant main effect of signal duration ($F_{3,51}=28.95$, $p<0.0001$), a main effect of age ($F_{1,17}=26.60$, $p<0.0001$), and a significant interaction between duration and age ($F_{3,51}=4.32$, $p<0.01$). The slope of the line fitted to thresholds as a function of age rose from -2.41 dB/yr for the 8-ms signal to -0.91 dB/yr for the 512-ms signal. These slopes were significantly different from zero for all four durations ($p<=0.002$). Contrasts performed on this interaction indicate that the first fourfold increase in signal duration resulted in a significant change in the effect of age (8 vs 32 ms; $F_{1,17}=6.76$, $p<0.05$), but that subsequent increases did not ($p>=0.05$). These results are consistent with the results of the group analyses. That is, there was an effect of listener age and signal duration at both frequencies, but the interaction between age and duration was limited to the lower, 1625-Hz signal frequency. The greater temporal integration of younger children at 1625 Hz can be attributed to a relatively large age effect for thresholds in the 8-ms signal condition.

The threshold elevation for younger children is consistent with the general finding of poorer performance of school-aged children as compared to adults in a wide range of psychophysical tasks (Irwin *et al.*, 1985; Wightman *et al.*, 1989; Grose *et al.*, 1993; Hall and Grose, 1994; Trehub *et al.*, 1995; Buss *et al.*, 1999; Hartley *et al.*, 2000). The hypothesis tested by the current experiment was that temporal integration would be greater for younger listeners, reflecting non-optimal temporal weighting of the output of a sliding temporal window. The finding of comparable temporal integration across age groups at 6500 Hz fails to support this hypothesis. At 1625 Hz, however, there was evidence that young children benefited more from longer signal presentation than either older children or adults. Temporal integration was approximately 4 dB larger in younger children than older children, a result due to relatively greater threshold elevation for the briefest signal duration. Such a result could indicate that children are relatively poor in optimally weighting the output of the monaural temporal window with respect to the timing of the signal, but only at the lower of the two signal frequencies tested here.

The finding of a duration-by-age interaction at 1625 Hz but not at 6500 Hz was not anticipated at the outset of this study. In fact, it could be argued that such an interaction should theoretically be more likely to occur at the higher stimulus frequency, where the briefest signal duration (2 ms) was tested. This signal duration was judged to be short enough with respect to the monaural temporal window that an inaccuracy in temporal integration could be observed, whereas the briefest signal at 1625 Hz (8 ms) could be sufficiently long relative to the monaural temporal window to obscure inaccuracies in monitoring its output. The present finding of frequency effect in the development of temporal integration will be considered along with previous relevant developmental findings in the general discussion section, below.

III. EXPERIMENT 2

A. Methods

1. Listeners

A group of 20 children ranging in age from 5.8 to 10.3 years (mean=7.7 years) was recruited, including nine females. Nine children were younger than 7 years of age. The adult group was composed of ten listeners, ranging in age from 18.7 to 45.6 years (mean=30.2 years), including six females. The children were recruited by flyers posted in the immediate medical/research community and in local schools. All of the children were in the age-appropriate grade in school. The adult listeners all responded to emails or flyers and were mainly university students. Twelve of the child listeners and six of the adult listeners had previously participated in experiment 1. All listeners had normal-hearing sensitivity as defined by pure-tone detection threshold of 20 dB HL or better at octave frequencies from 250 to 8000 Hz (ANSI, 2004). None of the listeners had a history of chronic ear disease or a history of speech, language, or learning disorders. All listeners were paid for participation.

2. Stimuli

The masker was a Gaussian noise, lowpass filtered at 3000 Hz using a fourth order Butterworth filter. In the 0-dB reference condition, this masker played continuously with the exception of 10-ms temporal gaps, separated by 100 ms. During the "on" portion of this modulation, the masker had a spectrum level of 30 dB. The boundaries of the gaps were effectively instantaneous, shaped only by the 3000-Hz lowpass filter. In the remaining masker conditions the level of the central 50 ms of each 100-ms pulse was manipulated. In the −6-dB condition the level of that central 50-ms portion was reduced by 6 dB, and in the +6-dB condition it was incremented by 6 dB. These level transitions were also effectively instantaneous, shaped only by the filter. The bottom portion of Fig. 3 shows a 300-ms sample of the masker envelope associated with the −6 dB masker condition, plotted as a function of time. The −6-, 0-, and +6-dB conditions will be referred to as "level transition conditions."

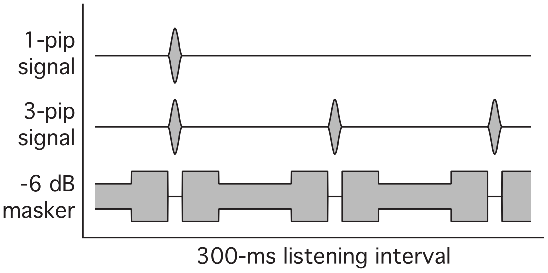

FIG. 3. Schematic representation of the stimuli for the −6-dB level transition condition.

The signal was a 1000-Hz tone, ramped on and off with 5-ms raised-cosine ramps and no steady state. When present, each signal pip was temporally centered in a 10-ms masker gap. In the one-pip signal conditions, the signal was synchronous with the first 10-ms gap in the listening interval. In the three-pip signal conditions, those pips occurred synchronous with the first three consecutive gaps after the listening interval commenced. No attempt was made to coordinate the onset of the listening interval and the phase of masker amplitude modulation. The timing of signal presentation relative to masker gating is illustrated in Fig. 3.

3. Procedures

Signal thresholds were estimated in a two-down, one-up adaptive track estimating 71% correct (Levitt, 1971). Prior to the first two track reversals the signal level was adjusted in steps of 4 dB, reduced to 2 dB for the last six reversals. Each track continued for a total of eight reversals. Threshold estimates were computed as the mean signal level at the last six track reversals. Three such estimates were obtained in each condition, with a fourth collected in cases where the initial three estimates spanned a range of 3 dB or more. All thresholds were obtained blocked by condition, with conditions visited in a different random order for each observer. The listening interval was 300 ms, and the inter-stimulus interval was 500 ms. Other aspects of the stimulus presentation and subject interface were as described in experiment 1. As in the previous experiment testing was completed in a single 1-h session for adults, whereas children took two such sessions to complete all conditions.

B. Results and discussion

Figure 4 shows the average thresholds for one-pip and three-pip conditions, plotted separately for adults, children

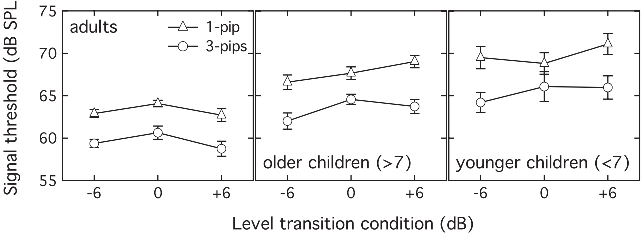

FIG. 4. Mean thresholds (dB SPL) measured for three level transition conditions, plotted separately for the two signal conditions (one pip and three pips). Error bars show ± one standard error of the mean. Circles show thresholds for three pips and triangles show thresholds for one-pip conditions. The left panel shows the results of the adults, the middle panel shows results of the children older than 7 years, and the right panel shows the results of the children younger than 7 years.

older than 7 years of age, and children younger than 7 years of age. Data are shown as a function of the level transition condition (−6, 0, and +6 dB). Symbol shape reflects the number of pips, either one (triangles) or three (circles). The error bars indicate ± one standard error of the mean. Mean thresholds were lower for the three pips than the associated one-pip condition in all three level transition conditions and all listeners, with only one exception: the mean 0-dB thresholds for one 6.9 year old child were 1.3 dB lower for the one-pip than the three-pip condition, a result plausibly attributable to measurement error.

Results of the adults will be considered first. Mean thresholds for the one-pip condition ranged from 62.7 to 64.1 dB sound pressure level (SPL), which is generally consistent with results reported by Viemeister and Wakefield (1991). The thresholds for the three-pip condition were approximately 3.6 dB lower than those for the one-pip conditions. As shown in Fig. 4, the +6- and −6-dB masker level transition conditions led to lower thresholds compared with the constant-level masker for both one-pip and three-pip conditions. To compare the thresholds measured for the three level transition conditions, a repeated-measures ANOVA was performed with three levels of level transition (−6, 0, and +6 dB) and two levels of number of pips (one pip and three pips). There was a main effect of level transition ($F_{2,18}=6.64$, $p<0.01$) and a main effect of number of pips ($F_{1,9}=119.03$, $p<0.001$). The interaction was not significant ($F_{2,18}=0.43$, $p=0.66$). A *post-hoc* test with Bonferroni correction indicated that thresholds were significantly higher in the 0-dB level condition than in either the +6- ($p<0.05$) or −6-dB ($p<0.001$) level transition conditions. Such an effect did not occur in the results reported by Viemeister and Wakefield (1991). That study showed that signal detection thresholds were not affected by changes in masker level regardless of the number of signals. It is possible that this apparent inconsistency is related to stimulus factors. An important feature of the current study is that the masking noise was presented continuously throughout a threshold run. In contrast, the masker was presented only during the observation intervals in Viemeister and Wakefield's (1991) study. It is possible that the temporal pattern of the continuous masking noise used here provided cues that were used by adults to aid detection of the signal. For example, the masker transitions could have served as landmarks to reduce temporal uncertainty with regard to signal presentation (see further discussion below). Another possible reason for the discrepancy in results across studies is related to listener factors. The adult listeners in Viemeister and Wakefield's (1991) study received extensive training before data collection, whereas all listeners in the current study had relatively limited psychoacoustic listening experience.

The threshold pattern for the children was somewhat more complex than that of adult listeners (see Fig. 4). For older children, mean thresholds in the one-pip condition ranged from 66.6 to 69.0 dB SPL. For younger children, mean thresholds in the one-pip condition ranged from 68.8 to 71.1 dB SPL. For both groups of children thresholds for the three-pip condition were lower than those measured for one-pip condition by an average of approximately 4.3 dB. In contrast to adult data, the effect of masker level transition on thresholds appeared to be different for one-pip and three-pip data. In contrast to the results of experiment 1, mean performance of the younger and older children was similar relative to the standard error of the mean (Fig. 4). A repeated-measures ANOVA was performed on child thresholds, with three levels of level transition (−6, 0, and +6 dB), two levels of number of pips (one pip and three pips), and two levels of group (younger and older children). This analysis resulted in a main effect of level transition ($F_{2,36}=9.37$, $p<0.001$), a main effect of number of pips ($F_{1,18}=197.35$, $p<0.0001$), but no effect of group ($F_{1,18}=2.51$, $p=0.13$). There was a significant interaction between level transition condition and number of pips ($F_{2,36}=9.71$, $p<0.0001$), but none of the interactions with group approached significance ($p\geq 0.38$). Simple effects' testing (Kirk, 1968) indicated that the interaction between level transition condition and number of pips was due to the fact that the threshold for the one-pip condition was higher in the +6-dB condition than either the 0-dB condition or the −6-dB condition ($p<0.01$), but that the threshold for the three-pip condition was lower in the −6-dB condition than either the 0- or the +6-dB condition ($p<0.05$). Repeating these group analyses using a general linear model with age as a continuous variable likewise failed to show a significant effect of age. Interpretation of these results is tempered somewhat by the significant heteroscedasticity of the data (Box's $M=57.65$, $p=0.025$), consistent with greater variance in the thresholds of younger children. We therefore also performed a non-parametric test (the Mann–Whitney U) to examine possible differences in thresholds for the two groups of children. This test indicated no significant difference between younger and older children ($p>0.05$) for any of the conditions. Based on these statistical results and visual inspection of the data, it was decided to perform subsequent analyses with the data of all child listeners pooled into one group.

A possible interpretation of the relatively poor performance for the one-pip signal in the +6-dB condition is that children were poor at listening in a temporally selective manner when the single pip was presented in the context of the relatively high-level masker bursts in the +6-dB conditions. For example, the +6-dB noise bursts could have resulted in distraction or confusion that reduced sensitivity to the signal. A possible interpretation of the relatively good performance

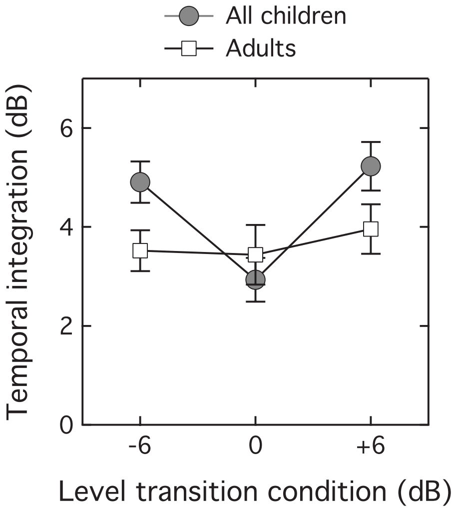

FIG. 5. Mean temporal integration (dB) calculated for three level transition conditions plotted separately for the two subject groups, as indicated in the legend. Error bars show ± one standard error of the mean.

in the three-pip, −6-dB condition is related to the temporal landmark account discussed above with respect to the adult data. That is, in the three-pip, −6-dB condition, children may have been able to improve performance by using the masker level transitions to reduce temporal uncertainty. It is possible that such an effect was not evident for the children in the three-pip, +6-dB condition because of an offsetting effect, where children are deleteriously affected by the distraction or confusion effects associated with the +6-dB masker bursts. By this account, the level transitions associated with the +6-dB increments could have had both (1) an advantageous effect related to the reduction of temporal uncertainty regarding the timing of the signal and (2) a disadvantageous effect related to difficulty in processing the energy increase due to the signal in the context of the relatively high-level (+6-dB) energy transitions of the masker. Note that there is no evidence for a temporal cueing effect in the children for the one-pip conditions. It is unclear why temporal cuing might benefit performance with the three pips but not the one-pip signal. It is possible that the ability to use such temporal cues is generally reduced in children and that multiple signals which more clearly form a spectro-temporal pattern are necessary to elicit such an effect in children.

We now consider differences between the adults and children in more detail. In terms of the masked thresholds, an obvious finding was that the thresholds of the children were higher than those of the adults (see Fig. 4). This difference was 4–6 dB in most conditions, but as high as 6–7 dB in the +6-dB level transition condition, which is considerably greater than the standard error of the mean associated with the threshold estimates (see Fig. 4). As discussed above, these results could suggest that children have a relatively poor ability to listen in a temporally selective manner in the context of the +6-dB masker bursts. Further insights into the differences between adults and children can be gained by examining the pattern of temporal integration derived from the masked thresholds. Figure 5 shows the amount of temporal integration, calculated as the difference in one-pip and three-pip thresholds, plotted separately for children and adults. The open symbols indicate data obtained from adults, while the filled symbols indicate data obtained from children. The error bars span ± one standard error of the mean across all listeners in each group. As indicated in Fig. 5, both groups showed positive temporal integration for all three conditions. The repeated-measures ANOVA was performed to compare integration between children and adults with two levels of group (child and adult) and three levels of level transition (−6, 0, and +6 dB). There was a significant main effect of level transition ($F_{2,56}=5.20$, $p<0.01$), but no main effect of group ($F_{1,28}=2.14$, $p=0.15$). The interaction between group and level transition was not statistically significant ($F_{2,56}=2.74$, $p=0.07$). There was no evidence of heteroscedasticity in the estimates of integration (Box's $M=3.75$, $p=0.78$). Overall, the results show no indication of reduced temporal integration for the children tested in this paradigm. One question of interest in this particular paradigm was whether children might be worse than adults in integrating signal energy that was temporally separated by relatively high masker energy (+6 dB). Figure 5 shows no indication of such an effect. An underlying reason for this could be related to the relatively poor thresholds of the children for the single tone presented in the +6-dB masker (see Fig. 4). That result suggests that the +6-dB masker does pose a difficulty for the children, but does not have a specific deleterious influence on the ability to integrate signal energy that is dispersed over time in these listeners.

IV. GENERAL DISCUSSION

The aim of the present study was to provide insights about aspects of temporally selective monaural hearing in children. Results of one previous study (Hall *et al.*, 2007) were consistent with an interpretation that children tended to assign the highest decision weights to the output of a sliding temporal window slightly after the optimal temporal epoch for detection based on binaural cues. One goal of the present study was to investigate whether this is a general feature of audition that applies also in monaural hearing. In experiment 1, masked thresholds were measured for a pure-tone signal at 1625 or 6500 Hz as a function of signal duration. If children were poor in weighting the output of the monaural temporal window with respect to the timing of the signal, then their thresholds should have been particularly high for the briefest signal duration tested. Results of experiment 1 indicated that children did not show particularly poor performance at the briefest signal durations for 6500 Hz, but did at 1625 Hz. Furthermore, at 6500 Hz, temporal integration was similar for adults and children, but at 1625 Hz temporal integration was larger for younger children than older children and adults. Overall, the results of experiment 1 were consistent with an interpretation that children in the age range tested here have a frequency-specific deficiency in the ability to listen in a temporally selective manner when detection is based on monaural cues.

The relatively poor performance of young children in detection of a brief, 1625-Hz signal could reflect a poor ability to focus attention on auditory cues at the temporally optimal time epoch. This might be modeled using an adult-like temporal window (e.g., Moore *et al.*, 1988; Plack and Moore, 1990), but basing threshold predictions on the output that temporal window output *after* the epoch associated with the best cue quality. Although it is unclear why this result would be restricted to low frequencies, it should be pointed out that developmental frequency effects have been reported previously. For example, several studies of infants and school-aged children have found evidence of earlier maturation of threshold sensitivity at high frequencies as compared to low frequencies (e.g., Olsho *et al.* 1988; Trehub *et al.*, 1988). Furthermore, the findings of Berg and Boswell (1999) with 7 month old infants suggested that this frequency-specific developmental effect for signal detection was duration-specific, consistent with the result that children showed relatively large temporal integration at low frequency, but more adult-like temporal integration at high frequency. Additionally, the results of Grose *et al.* (1993) were consistent with an interpretation that temporal resolution, measured by the ability to detect a tone presented in an amplitude modulated narrow band of noise, appeared to approach maturity by age 6 years for a center frequency of 2 kHz, but not until age 10 years for the lower center frequency of 500 Hz. It is possible that the developmental frequency effect observed in this and in previous studies have common underpinnings, a possibility that should be considered in future research.

In experiment 2, detection thresholds were measured for one and for three brief tone pips that were presented in the 10-ms gaps of a continuous, amplitude modulated noise masker. The level of the masking noise between the 10-ms gaps was either held at a constant level (0 dB), incremented (+6 dB), or decremented (−6 dB). Results showed that both adults and children had lower thresholds for three pips than for one-pip conditions. The interpretation of the second experiment is somewhat complex with respect to the question of the ability of children to listen in a temporally selective manner. One issue addressed by the paradigm is the ability to process brief signals that are separated in time, wherein adult-like temporal integration depends upon the selective combination of epochs where the signal-to-noise ratio is relatively high. With regard to this ability, the children tested here appeared to perform relatively well, with little, if any, indication of reduced temporal integration when compared to adults. Nevertheless, the results indicated that, under some conditions (e.g., one pip, +6-dB level transition condition), the children had some difficulty in selective temporal processing. Specifically, their performance was relatively poor when attempting to detect a brief signal in the context of relatively high-level masker bursts. This result could be summarized in terms of relatively poor sensitivity in detection of a brief low-frequency tone, but adult-like ability to combine information from multiple presentations of a brief tone. This result is similar to that reported by Berg and Boswell (1995) in their study of temporal integration of brief, temporally separated 500-Hz tone bursts in 7 month old infants.

One unexpected finding of experiment 2 was that the thresholds of the adult listeners were generally better in the −6- and +6-dB condition as compared to the 0-dB condition. This finding is inconsistent with the findings of Viemeister and Wakefield (1991), who reported that the level transition had no effect on thresholds for a gated masker that was otherwise similar to the continuous masker conditions of the present study. The discrepancy of results may reflect a form of temporal cueing associated with the continuous masking noise used in the current study. Such an effect might arise if the abrupt level transitions in the −6 and +6 dB conditions served as local temporal landmarks that improved the observer's ability to monitor the stimulus for signal cues in a temporally specific way. This would be consistent with the results of previous studies showing that the detection of brief signals can improve under stimulus conditions incorporating acoustical timing cues that are temporally proximal to the signal presentation (Chang and Viemeister, 1991; Jones *et al.*, 2002; Wright and Fitzgerald, 2004).

Whereas the results of the adult listeners were consistent with the use of temporal "landmark" cues for both the one-pip and three-pip transient masker conditions, the results of the children were consistent with the use of such temporal cues only for the three-pip, −6-dB condition. These cues appeared to be less effective in other conditions, and for the one-pip, +6-dB condition, the presence of a transient change in masker level appeared to elevate thresholds. This wide range of results across transient masker conditions could be related to recent findings of Werner *et al.* (2009). That study showed that introduction of an acoustic cue just prior to the listening interval improved adults' detection thresholds, but elevated thresholds of infants. A second experiment in that series showed that infants appear to form temporal expectations based on the presence of an interval cue, as indicated by the finding of poor performance when that expectation is violated. These results could be interpreted as indicating that the ability to make use of temporal landmark cues develops over time, and that the presence of landmark cues can introduce added masking in some cases. Development in the ability to make use of temporal landmark cues could be related to the processes by which the human auditory system parses ongoing streams of acoustical energy into separate signal and noise sources, sometimes referred to as auditory scene analysis (e.g., Leibold and Neff, 2007), though interpretation of the present results in terms of scene analysis requires further investigation.

One common feature of results of experiment 1 and 2 is that children often showed higher masked thresholds than those of adults. That difference was between 1 and 3 dB in experiment 1 and 4–5 dB or higher in experiment 2. As noted previously, poor use of temporal landmark cues may have contributed to some of the relatively high thresholds of children in some conditions of experiment 2. However, a more general source of the threshold differences may have been related to the different masking paradigms involved in these two experiments. In experiment 1, the signal was presented in simultaneous masking noise. In experiment 2, however, the signal was always presented in a 10-ms temporal gap of the masking noise. Therefore, the masking was simultaneous in experiment 1 but non-simultaneous in experiment 2. As noted in previous studies (Buss *et al.*, 1999; Hartley *et al.*, 2000), the difference in masked thresholds between children and adults can be much greater for non-simultaneous masking than for simultaneous masking. Hartley and Moore

(2002) have speculated that the poor thresholds of children in non-simultaneous masking conditions arises due to an interaction between poor processing efficiency and stimulus level effects related to basilar membrane compression, a hypothesis that received support from the work of Hill *et al.* (2004). The difference in masking paradigms could also explain the unexpected finding that younger children had higher thresholds than the older children for the 1625-Hz conditions in experiment 1 but that the thresholds of the younger and older children did not differ significantly for the results of experiment 2. It has been shown that individual differences are smaller for simultaneous masking than for non-simultaneous masking (Wilson and Carhart, 1970; Buss *et al.*, 1999). Increased between-observer variability in non-simultaneous masking could be responsible for the failure to find a significant difference in masked thresholds between the younger and older children tested in experiment 2.

V. CONCLUSIONS

Experiment 1 showed that young children had more temporal integration than adults for a 1650-Hz tone, due to a relatively poor threshold for the briefest stimulus duration tested (8 ms). This finding was consistent with previous results from a binaural hearing paradigm (Hall *et al.*, 2007), and also consistent with an interpretation that young children are poorer than adults in optimizing the temporal weighting of the output of the monaural temporal window with respect to the timing of the signal. However, for a 6500-Hz signal, temporal integration was comparable across the ages tested. These results suggest that the development of temporally selective listening may be frequency specific.

Temporal integration measured in experiment 2 was comparable across age groups, a result indicating that children were able to combine signal energy that was dispersed in time and separated by masking noise of varying level. However, the findings of experiment 2 indicated that children showed evidence of reduced temporal selectivity under some conditions. Specifically, compared with adults, children showed a reduced ability to listen in a temporally selective manner when detecting a signal burst in the context of +6-dB masker bursts.

Adults showed evidence of an ability to utilize temporal landmark cues in detecting one or three brief signals presented in continuous amplitude modulated masking noise. Children demonstrated evidence of this ability only in the three-signal case.

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