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Factors affecting the processing of intensity in school-aged children

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Abstract

Purpose—Thresholds of school-aged children are elevated relative to those of adults for intensity discrimination and amplitude modulation (AM) detection. It is unclear how these findings are related, or what role stimulus gating and dynamic envelope cues play in these results. Two experiments assessed the development of sensitivity to intensity increments in different stimulus contexts.

Method—Thresholds for detecting an increment in level were estimated for normal-hearing children (5–10 yrs) and adults. Experiment 1 compared intensity discrimination for gated and continuous presentation of a 1-kHz tone, with a 65-dB-SPL standard level. Experiment 2 compared increment detection and 16-Hz AM detection introduced into a continuous 1-kHz tone, with either 35- or 75-dB-SPL standard levels.

Results—Children had higher thresholds than adults overall. All listeners were more sensitive to increments in the continuous than the gated stimulus and performed better at the 75- than the 35-dB-SPL standard level. Both effects were comparable for children and adults. There was some evidence that children's AM detection was more adult-like than increment detection.

Conclusions—These results imply that memory for loudness across gated intervals is not responsible for children's poor performance, but that multiple dynamic envelope cues may benefit children more than adults.

INTRODUCTION

Studies of auditory intensity discrimination in children have introduced a wide range of possible developmental trends. For example, Berg and Boswell (2000) reported adult-like performance by 3 years of age, while others have reported a protracted period of development up to or beyond 10–12 years of age (e.g., Maxon & Hochberg, 1982). One procedural factor that could play an important role in the variability across studies is the use of gated vs. continuous stimuli (Berg & Boswell, 2000; Werner & Marean, 1996). For a gated stimulus, the listener must retain a memory of the loudness associated with each interval and compare percepts across intervals separated in time. In the case of a continuous stimulus, on the other hand, the task can be performed based on detecting a within-interval *change* in loudness. Detecting an intensity increment in an ongoing sound does not require the listener to compare the loudness associated with stimuli in separate intervals, potentially reducing the memory requirements of the task. The present study sought to clarify the role of memory in the development of intensity discrimination in school-aged children.

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For intensity discrimination tasks with two or more gated intervals, performance in adults is thought to rely on two types of memory: sensory and context coding (Durlach & Braida, 1969). Sensory memory is a vivid, modality-specific memory which lasts ~10–20 seconds after stimulus exposure and decays in a logarithmic fashion (Cowan, 1988; Laming & Scheiwiller, 1985). Context coding, on the other hand, is associated with a more stable memory trace, in which some sensory detail is lost; it is based on a comparison of the target stimulus with previously presented stimuli. Berliner and Durlach (1973) measured intensity discrimination in adults for pairs of tones as a function of the inter-tone delay, with the level of the standard tone either fixed or roved in an unpredictable way on a trial-by-trial basis. They found that the delay between pairs of tones in a trial had a larger effect when the standard level was roved than when it was fixed. This result is consistent with the idea that the decay of sensory memory has a large effect when level rove requires the listener to compare stimuli within a trial. In the absence of rove, however, listeners seem to rely in part on context coding, which reduces their susceptibility to memory decay.

Performance on a wide range of memory tasks improves over childhood and into early adolescence (Gathercole, 1998), including tasks relying on sensory memory. For example, Keller and Cowan (1994) showed a difference between 6–7 year olds and adults in a task relying on sensory memory for tone pitch. That study involved two stages of testing. In the first stage, pairs of tones separated by 2 sec were presented, and their frequency separation was adjusted to estimate the Δf associated with 84% correct. In the second stage, the Δf for each listener was fixed, and the duration of the inter-tone interval was adjusted to estimate points on the psychometric function associated with 84% and 71% correct. The 84% threshold was near 2 sec for all listeners, as expected based on the first stage of testing. The 71% threshold, however, was significantly shorter for the 6–7 year-olds than the adults. This result was interpreted as reflecting a more rapid decay of sensory memory for pitch in young children than adults. In a subsequent study, Gomes et al. (1999) showed an analogous effect using mismatch negativity, supporting the idea that maturation in the persistence of sensory memory for pitch is independent of attention or strategy. Although there are fundamental differences in sensory memory for pitch and loudness (e.g., more rapid decay in memory for loudness; Clement, Demany, & Semal, 1999), it is possible that sensory memory for loudness follows a similar developmental time course to that observed for pitch.

In addition to maturation of sensory memory, development in the ability to carry out context coding could limit the performance of young children in intensity-based psychoacoustic tasks. Context coding is an active process, requiring attention, reliance on accumulated knowledge, and the use of specific listening strategies (Durlach & Braida, 1969). These factors have been implicated in the development of short-term memory generally (Chi, 1976; Cowan, Saults, & Elliott, 2002), and could play a significant role in performance of gated intensity discrimination. Further, immature sensory memory could reduce the attentional resources available for cognitive processing (Gomes, et al., 1999), including resources associated with context coding.

Expressed in $10\log(\Delta I/I)$, intensity discrimination in adult listeners is on the order of 4.5-dB better for continuous than gated stimuli (Green, Nachmias, Kearney, & Jeffress, 1979; Viemeister & Bacon, 1988). While this effect is not completely understood, one possibility is that it is related to the introduction of dynamic cues that reduce reliance on memory for loudness. The effect of stimulus gating on intensity discrimination in children is not known, but it is possible that the maturation of auditory memory for loudness could affect children's performance differently for gated and continuous stimuli. Some support for this hypothesis is garnered by reports that 3-year-olds are nearly adult-like at detecting increments in a continuous 55-dB-SPL, two-octave band of noise (Berg & Boswell, 2000), whereas intensity discrimination for a gated pure tone continues to develop well into childhood (Fior & Bolzonello, 1987; Jensen & Neff, 1993; Maxon & Hochberg, 1982).

Detection of amplitude modulation (AM) that is sufficiently low in rate to be temporally resolved by the auditory system is similar to intensity increment detection, in that both tasks are based on changes in stimulus level over time. As the rate of modulation increases, sensitivity to AM for a gated noise carrier declines (Viemeister, 1979), a result that is interpreted in terms of temporal resolution. Hall and Grose (1994) reported that while 4–10 year old children are less sensitive to AM of a noise carrier than adults, thresholds worsen as a function of increasing AM rate similarly in the two groups. In other words, the time constant associated with AM detection is similar in young school-aged children and adults. In conjunction with developmental effects for intensity discrimination, this observation is consistent with the hypothesis that both intensity discrimination and AM detection are limited by sensitivity to changes in intensity, with no additional developmental effects in temporal processing of AM.

Wojtczak and Viemeister (1999) demonstrated a strong relationship between increment detection and AM detection in adults. That study measured increment detection and detection of low-rate AM with a continuous pure tone at several stimulus levels. Increment detection thresholds (in units of $10 \log(\Delta I/I)$) were linearly related to AM detection threshold (in units of $20 \log(m)$, where m is a value 0–1 that represents modulation depth). This finding suggests that AM may be detected based on the discriminability of stimulus intensities at different points in the stimulus envelope, and not so much based on the dynamic transitions between these intensities. That is, envelope fluctuation itself may not be important in the detection of AM, apart from considerations related to temporal resolution. In contrast to this view, several groups have proposed that dynamic envelope changes are of critical importance to both AM detection and the detection of a level increment (Gallun & Hafter, 2006; Oxenham, 1997). In Gallun and Hafter (2006), adults detected an intensity increment imposed in the temporal center of a relatively long-duration tonal pedestal. Sensitivity was reduced by the introduction of AM maskers that were either at the target frequency or more than two octaves above the target frequency. These results were shown by Gallun and Hafter (2006) to be consistent with the use of dynamic transition cues, modeled using a modulation filterbank. In that modeling approach, detection was based on the outputs of bandpass filters acting on the stimulus envelope. Regardless of the exact mechanism responsible, the results of Wojtczak and Viemeister (1999) and Gallun and Hafter (2006) support the view that AM detection and increment detection are closely related and likely rely on similar processes.

The present set of experiments sought to clarify the factors responsible for relatively poor intensity discrimination in school-aged children compared to adults. The first experiment assessed the role of stimulus gating in the development of intensity discrimination abilities, by comparing performance for gated stimuli and for continuous presentation of the standard tone. If memory for loudness is a major contributor to the developmental effect observed for gated stimuli, then presenting the pedestal continuously should be more beneficial for child than adult listeners. The second experiment tested the hypothesis that intensity discrimination and AM detection are limited by the same factor(s) in children and adults. If this is incorrect and children benefit more from dynamic cues than adults — as they might if memory for loudness were a limiting factor — then this would be reflected in relatively better AM detection than intensity discrimination for children. An ancillary goal of this experiment was to evaluate the effect of level of the standard tone in the developmental effect observed for intensity-based tasks. Intensity discrimination for a pure tone improves as a function of signal level in adults, a result often attributed to spread of excitation and greater numbers of auditory channels providing cues to changes in intensity at higher presentation levels (e.g., Florentine & Buus, 1981). Some data indicate a maturation in the level effect for intensity discrimination (Maxon & Hochberg, 1982), with relatively greater benefit of increasing stimulus level in younger children. However, it is unknown whether presentation level affects increment detection and AM detection in an analogous way for children and adults.

I. EXPERIMENT 1

1. Methods

A. Listeners—Child listeners were 5.2 to 9.0 years of age (mean of 7.1 years), including 10 boys and 6 girls. Adult listeners were 19.8 to 51.7 years of age (mean of 29.9 years), including 5 men and 6 women. All had normal hearing, defined as thresholds of 15 dB HL or better at octave frequencies 250–4000 Hz (ANSI, 2010).

B. Stimuli—Stimuli were generated using a real-time processor (RP2, TDT), with dynamic parameters and experimental procedures controlled by MATLAB. Sounds were played out at a rate of 12.2 kHz (RP2, TDT), routed through a headphone buffer (HB7, TDT), and presented diotically with circumaural headphones (Sennheiser, HD650).

The stimulus was a 1000-Hz pure tone, played at a level of 65 dB SPL in the standard (no-signal) intervals, and the listener's task was to indicate the interval associated with a level greater than 65 dB SPL. The increment was 500 ms in duration, including 25-ms raised-cosine ramps, and it was defined in units of $10 \log(\Delta I/I)$. In the *continuous* condition, the standard tone played throughout a threshold estimation track, and the increment was gated on in the signal interval. In the *gated* condition, either the standard or the standard-plus-increment was gated on for 500 ms.

C. Procedures—Trials were presented as a three-alternative forced-choice. While a three-alternative task could tax the listener's memory more than a one- or two- alternative task, this procedure is often employed in studies with children because it does not require a sophisticated understanding of the perceptual features of the target signal. Rather than describing the qualities of the signal, the instructions are just to select the interval that sounds different from the other two, a task that is easily understood by almost all typically developing school-aged children. A 2-down 1-up stepping rule was used to estimate threshold, defined as the 71% correct point on the psychometric function (Levitt, 1971). Increment intensity was initially adjusted in 4-dB steps, reduced to 2 dB after the second track reversal, and tracks continued until eight reversals had been obtained. A threshold estimate was the average increment at the last six track reversals. Three such estimates were obtained and assessed for variability. If the initial three estimates spanned a range of 3 dB or more, then a fourth was collected. All thresholds in a condition were completed in a single block, and conditions were completed in random order. All estimates were averaged to compute the final threshold estimate for each listener in each condition. Listeners viewed an animated sequence marking the listening intervals, entered their responses on a touch-screen, and received only positive feedback.

All methods were approved by the Institutional Review Board at the University of North Carolina at Chapel Hill.

2. Results

Figure 1 shows the distributions of intensity discrimination thresholds for each group (as indicated on the abscissa) and each condition (as indicated above each panel). Median values are plotted with horizontal lines, boxes span the 25th – 75th percentiles, vertical lines indicate the 10^{th} – 90^{th} percentiles, and circles show the minimum and maximum thresholds. Visual inspection of this figure indicates that thresholds were higher in children than adults and higher for the gated than the continuous stimulus, but that the effect of gating was uniform across subject groups. This was confirmed with a repeated-measures analysis of variance (ANOVA) incorporating two levels of GROUP (child, adult) and two levels of COND (*continuous*, *gated*). There was a significant main effect of GROUP ($F_{1,25}$=18.20, p<0.001) and of COND ($F_{1,25}$=241.65, p<0.001), but no interaction ($F_{1,25}$=0.62, p=0.440).

Both groups were affected equally by gating when thresholds were represented in units of 10 log(ΔI/I). Intensity discrimination thresholds can be represented a number of different ways, however (Grantham & Yost, 1982; Green, 1988). The question of how best to characterize psychophysical intensity discrimination has received significant attention in the literature, with different studies supporting the use of 10 log(ΔI/I), 20 log(Δp/p), and ΔL (e.g., Buus & Florentine, 1991; Moore, Peters, & Glasberg, 1999; Shepherd & Hautus, 2007)[1]. Statistical analyses indicated that the interaction between group and condition was not statistically significant when thresholds were expressed in terms of 10 log(ΔI/I) or 20 log(Δp/p). The interaction was significant, however, when units of ΔL were used ($F_{1,25}$=10.90, p=0.003), with a larger effect of GROUP for gated than for continuous stimuli. There are reasons to prefer units of 10 log(ΔI/I) over units of ΔL in the present data set. Box's test indicated that covariance matrices were not significantly different across data sets in units of 10 log(ΔI/I) (M=1.39, p=0.739), but they were different when assessed in units of ΔL (M=10.34, p=0.025). Based on this observation, units of 10 log(ΔI/I) were used to characterize intensity discrimination in the remainder of this report.

Figure 2 shows intensity discrimination thresholds for individual child listeners, plotted as a function of age. Mean adult data are shown at the far right of the graph, with error bars spanning plus and minus one standard deviation. Symbol style reflects the stimulus condition, as defined in the legend, and vertical lines connect data points of individual listeners. In addition to the significant difference in thresholds across groups, there was also modest evidence of a developmental trend within the child group. Using a one-tailed significance criterion, the correlation with child age was significant for thresholds in the *gated* condition (r=−0.50, p=0.023) and for thresholds in the *continuous* condition (r=−0.45, p=0.041). The finding of a robust correlation between thresholds in these two conditions (r=0.77, p<0.001) suggests that individual differences may be a more important determinant of sensitivity than listener age. This possibility receives additional support from the finding of a significant partial correlation between thresholds in the *gated* and *continuous* conditions after controlling for child age (r=0.70, p=0.002, one-tailed). There was no correlation between the gated/continuous difference and child age (r=−0.09, p=0.36, one-tailed), indicating that there was no development in the ability to benefit from continuous stimulus presentation within the child group.

3. Discussion

Intensity discrimination thresholds for a 500-ms, 1-kHz tone are better for adults than school-aged children. Thresholds as a function of child age tended to improve over the range tested here (5–9 years), but this effect was modest. Robust correlations in the child data across conditions indicate consistent individual differences that are not accounted for by age. This finding suggests that while sensitivity improves over the age range tested here, there are individual differences in the time course of this development. This would be consistent with our previous data on pure-tone intensity discrimination in this age range (Buss, Hall, & Grose, 2006) and with the observation that particularly large individual differences are often observed at ages associated with rapid development (Werner & Gray, 1998).

Presenting the stimuli in gated intervals rather than in the context of a continuous stimulus elevates thresholds, but this effect is comparable for adults and children when results are represented in units of 10 log(ΔI/I). Previous work on intensity discrimination in adult listeners has demonstrated better performance for continuous than gated stimuli, with differences of 4.6 dB (Viemeister & Bacon, 1988) and 4.2 dB (Green, et al., 1979) under conditions comparable to those of the present study. These effects are similar to the average gated/continuous differences obtained with adults (4.9 dB) and children (5.4 dB) in the present experiment.

There are several possible explanations for the gated/continuous difference in adult listeners (reviewed by Turner, Zwislocki, & Filion, 1989). One is that presenting the stimulus continuously leads to loudness adaptation, such that there is better ability to encode a subsequent increase in intensity. There is no reason to believe that loudness adaptation differs in school-aged children and adults (Baruch, Botte, & Scharf, 1993), so adaptation is unlikely to introduce age effects in the tasks of the present experiment. Another explanation for the gated/continuous difference is the extra memory requirement associated with a gated stimulus (Durlach & Braida, 1969). Results of the present study do not support the hypothesis that memory for loudness, necessary for across-interval comparisons, limits the performance of children more than that of adults. This leaves open the possibility that the neural representation of intensity in the central auditory system is more variable in children than adults, a hypothesis considered by Buss et al. (2006).

II. EXPERIMENT 2

The goal of Experiment 2 was to assess the parallel between the developmental effects observed for intensity discrimination and AM detection. In adult listeners, Wojtczak and Viemeister (1999) demonstrated a linear relationship between increment detection and the detection of low-rate AM, with performance improving in both tasks as the presentation level is increased. This result suggests that the perceptual cue supporting performance of these two tasks may be highly related. It was hypothesized here that the same relationship would hold for child listeners. This prediction is based on the finding in Experiment 1 that children benefit to a comparable degree as adults from the introduction of dynamic cues for intensity discrimination with the use of continuous, rather than gated, stimuli.

A. Methods

1. Listeners—Child listeners were 5.4 to 9.5 years of age (mean of 7.1 years), including 8 boys and 8 girls. Adult listeners were 17.9 to 43.1 years of age (mean of 25.0 years), including 5 men and 6 women. All had normal hearing, defined as thresholds of 15 dB HL or better at octave frequencies 250–4000 Hz (ANSI, 2010). One of the child listeners had previously participated in Experiment 1.

2. Stimuli—Stimulus generation and presentation followed the procedures described for Experiment 1 (above), with the exception that stimuli were presented monaurally to the left ear. In the increment detection conditions (Δ*I-detect*), the standard stimulus was a continuous 1000-Hz pure tone played at a level of 35 or 75 dB SPL, and the listener's task was to indicate the interval associated with an intensity increment, defined in units of 10 log(ΔI/I). Each increment was 500-ms in duration, including onset and offset ramps. Ramps were 15.6-ms raised cosines, resembling the onset of the first period of modulation in the AM detection task.

For amplitude modulation detection (*AM-detect*), modulation was achieved by multiplying a 1000-Hz tone with a raised 16-Hz sinusoid, and the result was scaled to either 35- or 75-dB SPL. Modulation began and ended at envelope values associated with the standard intensity, with no further smoothing or ramping. In all cases, modulation began with a positive slope (i.e., approximately sine phase), such that the first envelope maximum occurred approximately 15.6 ms after modulation onset (1/4 of a period of 16-Hz AM). Target modulation lasted for approximately 500 ms and was embedded in a continuous tone. This listener's task was to indicate the interval associated with the amplitude-modulated stimulus. Modulation depth was defined in units of 20 log(m).

3. Procedures—Procedures closely followed those of Experiment 1. Thresholds were obtained in blocks by condition. At least three estimates were obtained in each condition, and a fourth was taken when the first three spanned a range of 3 dB or more. Conditions were completed in random order.

B. Results

Thresholds are plotted in Figure 3, with individual child listeners' results plotted as a function of age. The mean adult thresholds are plotted at the far right of each panel, with error bars spanning plus and minus one standard deviation. Symbols reflect the level of the standard, as indicated in the legend, and data for each child are connected with a vertical line. The two panels show results for increment detection (top) and modulation detection (bottom).

Increment detection will be considered first. For both levels, mean thresholds for child listeners were poorer than those for adults. This difference was, on average, 3.0 dB for the 35-dB level and 2.8 dB for the 75-dB level. This is comparable to the 3.5-dB difference across groups observed in Experiment 1 for the continuous stimulus presented at 65-dB SPL. Age group differences were assessed using a repeated-measures ANOVA, with two levels for each of two variables: LEVEL (low, high) and GROUP (child, adult). This analysis confirmed a main effect of GROUP ($F_{1,27}$=29.06, p=0.001). There was also a main effect of LEVEL ($F_{1,27}$=111.33, p<0.001), but there was no interaction between GROUP and LEVEL ($F_{1,27}$=0.04, p=0.849). This result indicates that the detection advantage associated with the higher-level standard was not significantly different in child and adult listeners, with an across-group average difference of 4.2 dB between the 35- and 75- dB thresholds. The data were examined for effects of age within the child group by performing an analysis of covariance (ANCOVA), with LEVEL as a between-listener variable and child AGE as a within-listener variable. The effect of AGE and the LEVEL by AGE interaction failed to reach significance (p>=0.138).

The bottom panel of Figure 3 shows results of the AM detection task. Thresholds for child listeners were poorer than adults' at both standard levels, with mean differences of 3.9 dB and 2.6 dB for the 35- and 75-dB SPL levels, respectively. Age group differences were assessed using a repeated-measures ANOVA, with two levels for each of two variables: LEVEL (low, high) and GROUP (child, adult). There was a main effect of GROUP ($F_{1,27}$=6.48, p=0.017) and a main effect of LEVEL ($F_{1,27}$=148.98, p<0.001), but no interaction between GROUP and LEVEL ($F_{1,27}$=0.61, p=0.443). As in increment detection, children performed more poorly than adults, but they benefited from increasing the level of the standard stimulus to the same degree. The average difference between thresholds for the 35- and 75-dB stimulus levels was 10.7 dB. The data were examined for effects of age within the child group by performing an ANCOVA. The effect of AGE and the LEVEL by AGE interaction failed to reach significance in this analysis (p>=0.394).

Figure 4 shows individual listener's increment detection thresholds (Δ*I-detect*) plotted as a function of their AM detection thresholds (*AM-detect*). Symbols indicate the level of the standard stimulus, as defined in the legend. Data for the two groups are plotted in separate panels. Lines were fitted to the data in each group by minimizing the sum of the squared error. The solid lines in both panels are the best fit to adult data, and the dotted line is the best fit to child data. The slopes fitted to these data are similar across groups, with values of m=0.37 for adult data and m=0.32 and for child data. This is somewhat lower than the value of 0.44 reported by Wojtczak and Viemeister (1999) for adults tested under comparable stimulus conditions. The y-intercept differs across groups. For adult data the intercept is −0.33 dB, and for child data it is 0.45 dB. These age effects are similar to those observed when lines are fitted to group mean data.

The significance of differences in line fits to adult and child data was assessed by fitting child data using the parameters characterizing adult data and then examining the residuals. There was no significant association between residuals and thresholds in the AM detection task ($F_{1,30}$=1.47, p=0.234), indicating that the slope of the data was well fitted by the adult slope estimate. The mean of the residuals was significantly different from zero (t_{31}= 5.80, p<0.001), however, reflecting the fact that the intercept fitted to adult data was not an optimal fit to the child data. These results can be interpreted as showing that the developmental effect is relatively greater for increment detection than for 16-Hz AM detection in the context of continuously presented stimuli.

C. Discussion

Increment detection thresholds measured in this experiment improved with level of the standard. For adults, mean thresholds were −6.2 and −10.4 dB at 35 and 75 dB SPL, respectively. For children, these values were −3.3 and −7.6 dB, respectively. These level effects can be compared to those reported by Rabinowitz *et al*. (1976), who compiled data of 15 studies measuring intensity discrimination as a function of stimulus level for a 1-kHz tone. Based on that review, the average expected change in thresholds between 35 and 75 dB SPL is on the order of 2.5 dB. This is less than the approximately 5-dB change found by Wojtczak and Viemeister (1999) and the 4.6 dB change obtained in the present study. Threshold improvement with increasing level has been described as the `near miss' to Weber's law because sensitivity to intensity increments is not constant relative to the level of the standard. It is widely accepted that the near miss is due to greater spread of excitation at higher stimulus levels, and hence a wider range of frequencies providing cues to changes in intensity (e.g., Florentine & Buus, 1981). The present results suggest that whereas school-aged children perform more poorly overall, they benefit from these additional cues to the same extent as adult listeners.

Previous data on the effect of stimulus level for intensity discrimination have shown that younger listeners tend to perform particularly poorly for low-level stimuli, such that the age effect is largest at the lowest presentation levels. Berg and Boswell (2000) measured increment detection for two-octave bands of noise in 1 to 3 year-olds and adults, and they found a greater age effect at low than at high presentation levels. Maxon & Hochberg (1982) found an analogous result for gated intensity discrimination of a 500-Hz tone. Comparing results across a group of 4 to 12 year-olds, the age effect was largest at the lowest stimulus level, equated in dB sensation level. However, this age effect was dominated by the pronounced effect of level for the youngest group of listeners (4-year olds); level effects were nearly identical for 6 to 12 year-olds. Data from the present and previous studies are consistent with the conclusion that level effects reach maturity between 4 and 6 years of age.

Like increment detection, modulation detection thresholds improved with increasing level in both groups, with an average difference of 10.7 dB between thresholds at the 35- and 75-dB-SPL presentation levels. This result is consistent with previous literature on adults (Kohlrausch, 1993; Wojtczak & Viemeister, 1999). As for increment detection, AM detection was worse for child than for adult listeners, with a mean group difference of 3.3 dB. The present results can be compared to those of Hall and Grose (1994), who reported a significant age effect for AM detection. In that study the stimulus was a continuous 75-dB-SPL Gaussian noise, bandpass filtered between 200 and 1200 Hz, and modulation was achieved via multiplication with a raise sinusoid. Modulation detection thresholds improved as a function of age: the child/adult difference was approximately 3.6 dB for 6–7 year olds, the mean age of listeners in the present experiment. That age effect for a noise carrier is consistent with the results obtained here for a pure-tone carrier.

The relationship between modulation detection and intensity discrimination for a continuous tone in the child data follows the same general trend as described previously in adult data – better sensitivity to AM is associated with better sensitivity to intensity increments (Wojtczak & Viemeister, 1999). There is evidence that AM detection may be less prone to developmental age effects, however, reflected in the offset in the intercept of the line relating these two variables. One reason for this could be related to the number of opportunities to hear a dynamic change in stimulus intensity; the AM detection task provides multiple opportunities to detect dynamic changes in intensity, whereas the increment detection task is associated with dynamic changes only at increment onset and offset. This explanation suggests that envelope fluctuation itself may be an important factor in children's AM detection, as contrasted with comparisons of stimulus intensities at different points in the stimulus envelope. The ability to benefit from multiple dynamic envelope transitions could be related to the benefit of `multiple looks' that is described in studies of temporal integration (Viemeister & Wakefield, 1991). There is some indication that children experience more temporal integration than adults when detecting a 1625-Hz tone (He, Buss, & Hall, 2010), and it is possible that integration of multiple looks in AM detection follows a similar trend.

III. GENERAL DISCUSSION AND CONCLUSIONS

At the outset of this study, it was hypothesized that children's intensity discrimination thresholds could be limited by memory to a greater extent for gated than for continuous stimuli. These limits could include immaturities in sensory memory, the ability to carry out context coding, or some combination of these factors. As previously observed in adults, intensity discrimination was better when the standard played continuously than when it was gated on and off in each listening interval. This benefit was seen to a comparable degree in the data of both adults and school-aged children. Since the continuous presentation introduces a within-interval cue, this result suggests that development of memory for loudness across intervals is not responsible for children's poor performance with gated stimuli. One possibility is that both sensory memory and context coding for intensity are mature in school-aged children. Another possibility is that such differences do exist, but that other factors dominate the results observed here. For example, whereas continuous presentation alleviates demands on the listener's memory for loudness, the listener must select from among three possible signal intervals. Near threshold, the ability to identify the target interval is improved by comparing cue strength across intervals. Development could affect the accuracy of this comparison. In either case, the present results imply that the large variability in developmental data for intensity discrimination (Exp. 1 of the present report; Buss, Hall, & Grose, 2009) cannot be attributed to the use of gated vs. continuous stimuli.

One generalization that might be drawn from the results of the first experiment is that dynamic, within-interval cues for intensity discrimination have a similar effect on children and adults. This conclusion is not fully consistent with results of the second experiment, however. For a continuous stimulus, detection of 16-Hz AM was relatively better in children than adults when compared to increment detection. That is, the more dynamic envelope changes characterizing the AM stimulus were easier for the children to detect than the relatively more stationary intensity increment. Therefore, a comparable gated/continuous difference across age groups (exp 1) is consistent with adult-like ability to benefit from dynamic envelope cues, but the relatively good performance on AM detection in children (exp 2) seems to indicate maturation of that ability.

One way to resolve this apparent conflict is to propose a different process for exploiting onset cues present for increment detection and modulation cues present for AM detection. There is a linear relationship in the data obtained for these measures within listener groups (Exp 2, Fig 4; Wojtczak & Viemeister, 1999), but there could nonetheless be important differences in the cues underlying these two tasks. Modeling work using the modulation filterbank speaks against this possibility, supporting the idea that increment detection and AM detection are based on the same underlying cues. However, that modeling has typically used relatively brief signals (e.g., <100 ms; Gallun & Hafter, 2006), and it is unclear whether these results would hold for longer duration stimuli (e.g., the 500 ms used here). Better performance in AM detection might occur if children benefit to a greater degree than adults from multiple looks for dynamic envelope features. Increment detection in a continuous stimulus provides a pair dynamic cues (an onset and offset), whereas AM detection for a 16-Hz rate provides eight such pairs of cues in a 500-ms listening interval. It has been proposed that integration of cues across modulation periods for continuous stimuli may not be optimal in adults due to temporal stimulus uncertainty regarding the onset of modulation (Sheft & Yost, 1990); one possibility is that children are more prone to `over integration' than adults, leading to a larger benefit for stimuli with ongoing AM. Greater integration of dynamic envelope cues in children is broadly consistent with the finding of greater temporal integration for detection of tones in children under some conditions (He, et al., 2010). Additional data on the temporal integration of AM would be required to confirm this interpretation, however.

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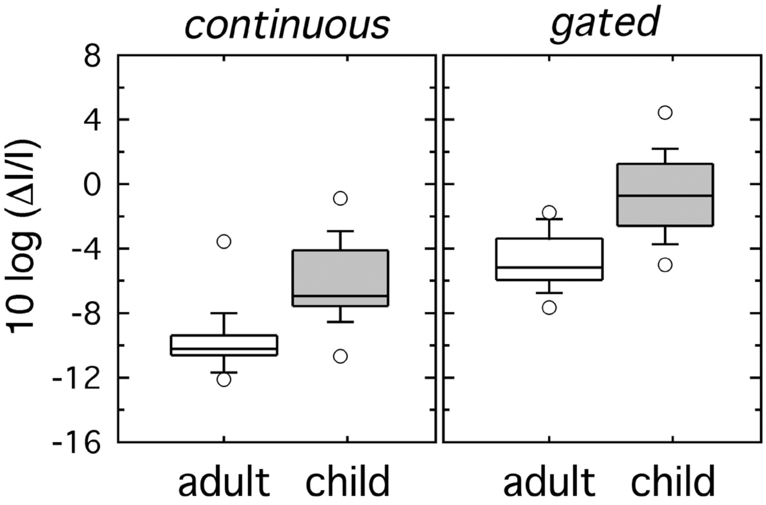

Figure 1.

The distributions of thresholds for increment detection with a continuous standard (left panel) and intensity discrimination with a gated presentation (right panel) are shown for children and adults. Horizontal lines indicate the median thresholds, boxes delineate the 25th – 75th percentiles, vertical lines indicate the 10th – 90th percentiles, and circles indicate the minimum and maximum thresholds.

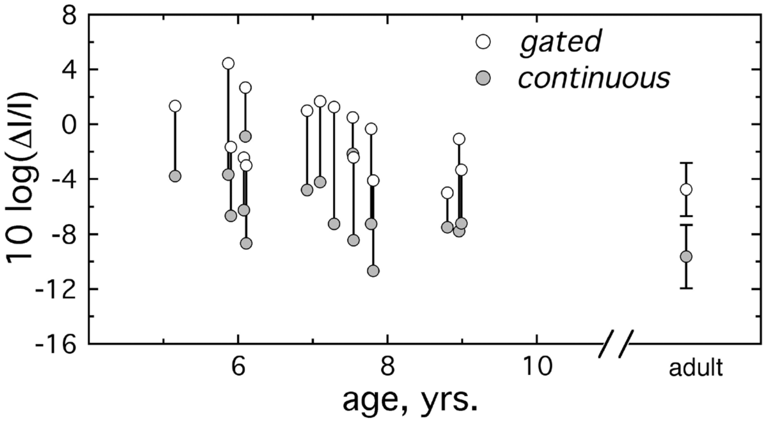

Figure 2.
Thresholds for individual listeners are plotted as a function of age for child listeners. Mean thresholds for adult listeners are indicated at the right of the figure, with error bars showing +/− 1 standard deviation. Thresholds for *gated* stimuli are plotted with open circles, and those for *continuous* stimuli are plotted with filled circles, as indicated in the legend.

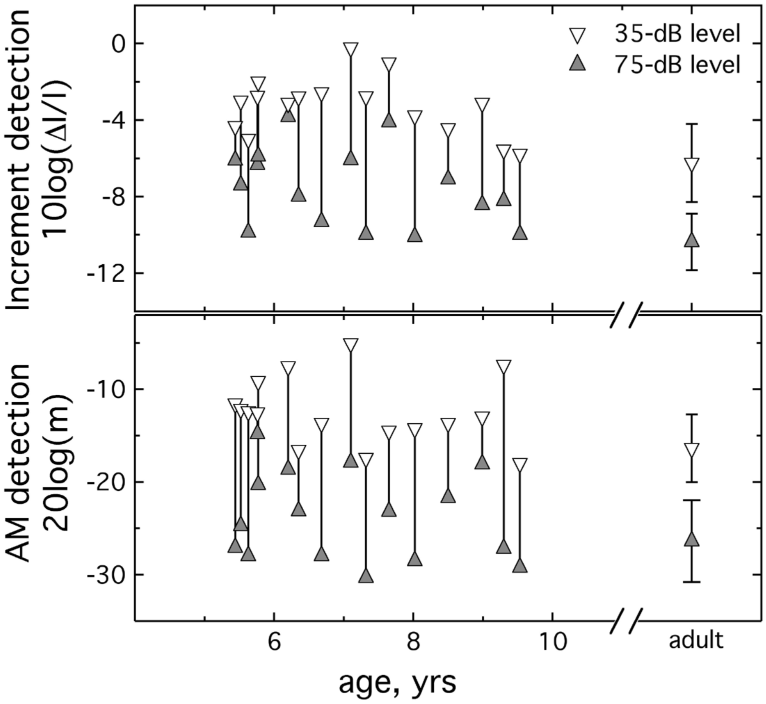

Figure 3.

Following the convention of Figure 2, threshold estimates are plotted for individual listeners as a function of age for child listeners. Mean thresholds for adult listeners are indicated at the right of the figure, with error bars showing +/− 1 standard deviation. The top panel shows results of the increment detection, and the bottom panel shows results of the AM detection task. Symbols indicate stimulus level, either 75 dB SPL (filled, up-pointing triangles) or 35 dB SPL (open, down-pointing triangles).

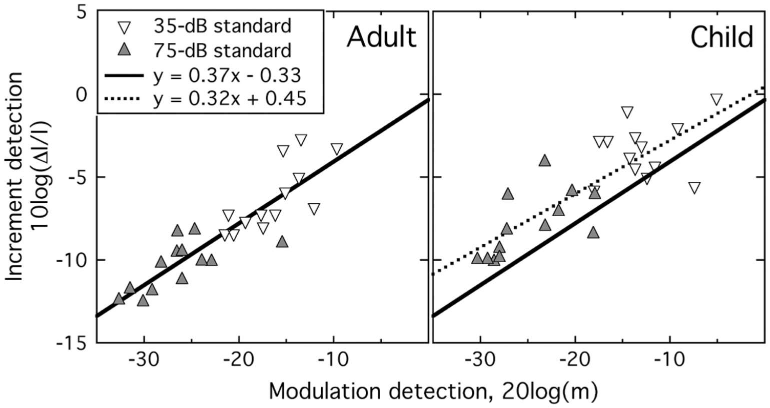

Figure 4.

Increment detection thresholds are plotted as a function of modulation detection thresholds for two signal levels. Symbols indicate stimulus level, which was either 75 dB SPL (filled, up-pointing triangles) or 35 dB SPL (open, down-pointing triangles). Adult data appear in the left panel, and child data appear in the right panel. The line fitted to adult data is indicated with solid lines in each panel. The best fit to child data is indicated in the right panel with a dotted line.