Noise increment detection in children 1 to 3 years of age

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Studies using burst comparison procedures to examine age-related changes in intensity discrimination have reported that the ability to discriminate differences in intensity does not reach maturity until late childhood. In the present study, developmental changes in intensity discrimination were examined in 1- to 3-year-old children, using an increment detection paradigm. Children and adults detected increments in a continuous standard presented at three levels ranging from 35 to 55 dB SPL. Adults were also tested at lower levels of the standard in order to permit age comparisons at equivalent sensation levels. Standard stimuli were two-octave bands of noise centered at either 400 or 4000 Hz, and increments were 200 msec in duration. Discrimination performance improved significantly with both age and level of the standard. For all age groups, performance was significantly better for high- than for low-frequency stimuli, but frequency-dependent differences in increment thresholds did not vary reliably with age. Age differences were largest at low levels of the standard. At the highest level (approximately 30 dB nHL), children's difference limens for both low- and high-frequency noise bands were adultlike by 3 years of age. These results suggest that the developmental time course of increment detection is more rapid than that previously reported in burst comparison studies.

Although the ability to detect a change in the level of a sound is one of the most basic auditory capacities, little is known about the time course of its development. The few studies that have examined intensity discrimination in young listeners indicate that performance is relatively poor during infancy and continues to improve well into childhood, but, as yet, there is no consensus on the age at which adultlike performance is achieved. The results of at least three studies suggest that the ability to discriminate differences in intensity matures relatively late. Both Faires and Lankford (1976) and Fior and Bolzonello (1987) determined children's intensity difference limens (DLs) for pure tones and found that performance continued to improve through at least 10 years of age. Similarly, Maxon and Hochberg (1982) reported a progressive improvement in the DL for tones through 12 years of age, the oldest group tested. In contrast to these findings, results reported by Jensen and Neff (1993) suggest a more rapid course of development. They used a video game format to obtain children's DLs for a 440-Hz tone and found that, for most children, performance was adultlike by 5 years of age.

Werner and Marean (1996, p. 95) have recently questioned whether the ability to discriminate differences in intensity develops at all during childhood. Citing differences in procedure across studies and the great variability in performance among young listeners, they suggested that the sensory mechanisms underlying intensity discrimina-

tion may mature early in life and that continued improvements in the discrimination performance of school-age children reflect the maturation of attention and cognitive abilities. Although the influence of such nonsensory factors cannot be completely eliminated in studies of auditory development, it may be reduced by the choice of paradigm. Burst comparison is the procedure that has been most commonly used in both the adult and the developmental literature. In this type of experiment, two sounds are presented in sequence, and the listener's task is to judge which of the two is more intense. This requires that he or she remember the first sound and compare its image with the second, occurring later in time. In a second type of paradigm, the listener detects brief increments in the level of a continuous sound. Because this task involves detection of the increment onset, rather than a comparison of sounds, performance should be less affected by immaturities in memory and cognition. Except at very low levels of the standard, adult DLs have been found to be consistently smaller in increment detection than in burst comparison paradigms (Viemeister, 1988). The reason for this difference is not completely understood, although both differential memory requirements and adaptation to the standard have been advanced as possible explanations (Turner, Zwislocki, & Fillion, 1989).

Two studies have employed the increment detection paradigm to examine intensity discrimination in infants. Schneider and Trehub (1985) measured the ability of 12-month-olds to detect increments in continuous broadband noise, and reported DLs of approximately 5 and 2.5 dB for standards of 40 and 60 dB SPL. These values can be compared with DLs of less than 1 dB typically found in adult listeners under similar conditions (Miller, 1947).

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More recently, Berg and Boswell (1998) determined DLs for detection of increments in low- and high-frequency noise bands in 7-month-old infants. They found DLs similar to those reported by Schneider and Trehub (1985) at higher levels of the standard, but for standards below approximately 30-dB sensation level (SL), infants' DLs were significantly less mature for low- than for high-frequency noise bands.

To date, no studies of increment detection have been reported in children older than 12 months. The present experiment was designed to extend previous work by examining increment detection in children 1–3 years of age. Standard stimuli were two-octave bands of noise centered at either 400 or 4000 Hz. They were presented continuously at three levels intended to cover the range from approximately 10 to 30 dB SL. One goal of the study was to describe developmental changes in increment detection during early childhood. A second was to determine whether the frequency gradient previously reported in 7-month-olds would also be evident in older children.

METHOD

Participants

Thirty-two children were tested in each of three age groups: 1-year-olds (mean age, 14 months; range, 12–15 months), 2-year-olds (mean age, 25 months; range, 24–27 months), and 3-year-olds (mean age, 38 months; range, 36–39 months). All were in good health and free of colds or ear infections when tested. Sixty-two additional children were seen in the laboratory but did not provide threshold estimates meeting the criteria for acceptance. These included 13 children at 1 year, 22 at 2 years, and 27 at 3 years of age. Of those children excluded from the final sample, 10 failed to meet training criteria, 43 were excluded because of fussiness or loss of interest in the visual reinforcers, and 9 either declined to participate or asked to terminate the session before testing was completed.

Forty-eight adults were also tested for comparison. The adult listeners were undergraduate students enrolled in introductory psychology courses, who received class credit for their participation.

Stimuli

The stimuli were bands of filtered noise, two octaves in width and centered at either 400 or 4000 Hz. They were generated by passing white noise through a TDT PF1 digital filter. Preprogrammed Butterworth filter functions yielded rolloffs of 36 and 60 dB/octave for low- and high-frequency noise bands, respectively. The filter output was divided into two channels. One channel provided the continuous standard; the other was passed through a cosine switch (TDT SW2) and a programmable attenuator (TDT PA4) and was added back to the first in phase, to produce an intensity increment. The continuous standard was presented at levels of 35, 45, and 55 dB SPL for both low- and high-frequency noise bands. Increments were gated with a rise/decay time of 5 msec and a duration of 200 msec. They were delivered in trains consisting of up to seven repetitions per trial. The onset-to-onset interval of individual bursts was 600 msec, resulting in a train approximately 4 sec in duration. All the stimuli were presented in sound field via a Bose model 100 loudspeaker. Sound levels, measured at the site of the listener's head by a Bruel and Kjaer 2235 sound level meter, did not vary more than ± 2 dB within the range of possible head positions.

Procedure

The children were tested with a visually reinforced operant procedure. One- and 2-year-olds were seated on their parents' laps in

the center of a sound-attenuated room, with a loudspeaker and three battery-operated toys in Plexiglas boxes located 90° to the right. For these age groups, head turns to the right on signal trials were considered correct detections and were reinforced by the brief activation of an animated toy. Three-year-olds were seated, either alone or in their parents' laps, with a large picture of a clown's face on a table in front of them and a loudspeaker and TV monitor located 90° to the left. They were instructed to "press the clown's nose whenever you hear the sound change." For 3-year-olds, correct responses were reinforced by briefly turning on the TV. Video reinforcement consisted of age-appropriate videotaped segments on 60% of the reinforced trials and the child's own video image on the remaining 40%. A supply of unusual hats and costume accessories was available, and children who wished to do so were able to view themselves on the TV monitor wearing these items.

One experimenter, seated directly in front of the participant, attempted to keep the child on task and initiated trials when the child was attentive and in midline orientation. A second experimenter, outside the chamber, observed the child on a TV monitor and made judgments on responses. During testing, the parent and the experimenter in the room with the child wore headphones and listened to recorded music or masking noise to eliminate possible sources of bias. Experimenters received a signal marking the observation interval on each trial but did not know when increments were presented.

The test procedure employed a single-interval, go/no-go paradigm. For 1- and 2-year-old children, signal and nonsignal trials occurred with equal probability. For 3-year-olds, who typically had low false alarm rates and listened attentively between signal presentations, the *a priori* probability of nonsignal trials was reduced to .3, to shorten the interval between reinforcements. Trials were presented in random order, with the restriction that no more than three trials of either type be presented consecutively. If the child responded during an observation interval, the experimenter outside the chamber pressed a button to record the response and terminate the interval. Observation intervals not terminated by a response were 4 sec in duration. Responses on nonsignal trials were recorded as false alarms and were not reinforced. If the child became obviously distracted during an observation interval, the trial was rejected.

The children within each of the three age groups were randomly assigned to experimental groups, each consisting of 8 listeners, and received both low- and high-frequency noise bands at a single level of the standard. For these groups, the standard was on when children entered the chamber and remained on continuously throughout the session. To provide an estimate of the SL of the standards, absolute thresholds were obtained for 200-msec low- and high-frequency noise bursts in additional groups of 8 listeners, resulting in a total of four experimental groups at each age. Four groups of adult listeners were tested under the same conditions for comparison. In addition, two groups of adults were tested at lower levels of the standard, to permit age comparisons at equivalent SLs. One group received a low-frequency standard of 10 dB SPL and a high-frequency standard of 15 dB SPL, corresponding to estimated SLs of 5 and 12 dB; for the second group, levels of the standard were 10 dB higher. Order of frequency conditions was counterbalanced across participants within each group.

Prior to testing, the children were required to meet a criterion of four consecutive correct responses, with the increment presented at a clearly audible level, usually 10 to 15 dB above the level of the standard. Two consecutive correct responses were required following within-session changes in frequency of the standard. Once this criterion had been met, an adaptive one-up, two-down tracking procedure was initiated. Level of the increment channel was initially set 5 dB [in terms of $20 \log(\Delta P/P)$, where P is sound pressure] above the level of the standard for children receiving the 45- and 55-dB SPL standards and 10 dB above the standard for children tested with the 35-dB SPL standard. For children in absolute threshold groups, initial level was set 30–35 dB above adult threshold for the

same stimulus. Step size began at 8 dB and decreased by half on subsequent up-down reversals until a minimum step of 2 dB had been reached. Only outcomes on signal trials contributed to alterations in the level of the increment. After the first reversal, probe trials with increment level set 10 dB above the current tracking level were presented every eighth trial, to provide an estimate of distraction or loss of interest in the visual reinforcers. On these trials, the visual reinforcer was presented at the end of the observation interval if the child did not respond. Probe trials were also presented as "reminders" after two consecutive failures to respond on signal trials. Tracking was terminated after five reversals, after a maximum of 50 trials, or if signal level exceeded a predetermined maximum, set 10 dB above the starting level. Threshold estimates were computed only for runs in which at least four reversals had been obtained. They were calculated as the mean level in the increment channel over the last three reversals and included all trials for which step size was 2 dB. This was converted to threshold ΔL [$=20 \log((P + \Delta P)/P)$], the level difference in decibels between the standard and the standard plus the increment. Criteria for acceptance of threshold estimates were intended to minimize the contribution of non-sensory variables. Thresholds were considered acceptable if (1) false alarms occurred on no more than one third of the nonsignal trials, (2) the child failed to respond on no more than one probe trial, and (3) the excursion of the staircase was less than 10 dB after the third reversal. Testing continued either until threshold estimates meeting the above criteria had been obtained for both low- and high-frequency noise bands or until the child's state precluded further testing. The session was terminated if the child expressed a desire to stop.

Adult listeners were tested under the same stimulus conditions for comparison. They were seated alone in the chamber, provided with a response box, and instructed to press a button whenever they heard the increment train. Observation intervals were unmarked, and intervals between trials varied randomly between 1 and 15 sec in duration. Lights within one of the Plexiglas boxes were briefly flashed as feedback for correct detections. All other procedures were identical to those described for the children.

RESULTS

Prior to statistical analysis, all the data were screened for homogeneity of variance, using Levene's test. For instances in which group variances were not homogeneous, the significance of differences among experimental conditions was assessed, using the Brown-Forsythe statistic (Dixon, Brown, Engelman, & Jennrich, 1990), which compensates for the effect of unequal variances by reducing the degrees of freedom.

Averaged across conditions, the mean number of trials required to obtain a threshold estimate was 33.0 for absolute and 33.8 for differential thresholds. Trials rejected because of distraction constituted 1.3%, 2.5%, and 0.5% of the total trials in 1-, 2-, and 3-year-old age groups, respectively. False alarm rates varied significantly with age [$F(3,112) = 15.98, p < .001$] but did not differ across levels or frequency bands. Mean false-alarm rates were .17, .18, and .10 for 1-, 2-, and 3-year-old children and .09 for adults.¹

Absolute Thresholds

Mean thresholds for 200-msec noise bursts presented in quiet are shown for each of the four age groups in the upper left panel of Figure 1. Error bars represent ± 1 stan-

dard deviation from the mean. In agreement with results previously reported for young listeners (Olsho, Koch, Carter, Halpin, & Spetner, 1988; Trehub, Schneider, & Endman, 1980), children's absolute thresholds were higher than those of adults and were higher for low- than for high-frequency noise bursts. Averaged across the three age groups, children's thresholds were approximately 23 and 17 dB above adults' for low- and high-frequency stimuli, respectively. These age differences in threshold are larger than those typically found for stimuli presented via headphones (Nozza & Wilson, 1984; Olsho et al., 1988) but well within the range of threshold differences reported for stimuli presented in sound field (Schneider, Trehub, Morrongiello, & Thorpe, 1986; Werner, 1992). A univariate analysis of variance (ANOVA), with age (four levels) as a between-subjects factor and frequency (two levels) as a within-subjects factor, revealed significant effects of both variables [age, $F(3,28) = 108.05, p < .001$; frequency, $F(1,28) = 57.30, p < .001$], as well as a significant age $\times$ frequency interaction [$F(3,28) = 3.47, p < .05$]. With adults excluded from the analysis, the main effects both of age [$F(2,21) = 5.31, p < .05$] and of frequency [$F(1,21) = 57.63, p < .001$] remained significant, but the interaction was not ($F < 1$), indicating that improvements in threshold between 1 and 3 years of age were approximately equivalent for both low- and high-frequency noise bursts. Single degree of freedom contrasts confirmed that, between 1 and 2 years of age, absolute thresholds improved significantly for both low-frequency [$F(1,21) = 6.60, p < .05$] and high-frequency [$F(1,21) = 6.05, p < .05$] stimuli but did not differ for 2- and 3-year-old age groups.

Differential Thresholds

The remaining panels of Figure 1 show mean DLs, represented in terms of ΔL , for standards ranging from 35 to 55 dB SPL. In general, discrimination performance was better for high- than for low-frequency stimuli and improved with both increasing age and level of the standard. A univariate ANOVA, including age (four levels) and level of the standard (three levels) as between-subjects factors and frequency (two levels) as a within-subjects factor, yielded highly significant main effects of all three variables [age, $F(3,34) = 79.57, p < .001$; level, $F(2,34) = 38.60, p < .001$; frequency, $F(1,34) = 48.38, p < .001$]. Significant age $\times$ level [$F(6,34) = 6.23, p < .001$] and frequency $\times$ level [$F(2,34) = 10.42, p < .001$] interactions, confirmed that both age and frequency differences were largest at lower levels of the standard, but differences between DLs for high- and low-frequency noise bands did not vary reliably with age [age $\times$ frequency, $F(3,34) = 1.33, p > .25$]. Separate ANOVAs for each age group yielded a significant main effect of frequency at all four ages [frequency for 1-year-olds, $F(1,21) = 6.88, p < .05$; for 2-year-olds, $F(1,21) = 23.18, p < .001$; for 3-year-olds, $F(1,21) = 15.36, p < .001$; for adults, $F(1,21) = 82.54, p < .001$]. Additional follow-up ANOVAs com-

Figure 1. Mean absolute thresholds for 200-msec noise bursts (upper left) and difference limens (ΔL) for 200-msec increments in continuous noise presented at each of three levels. The noise stimuli were two-octave bands centered at 400 and 4000 Hz. The age groups were 1-, 2-, and 3-year-old children and young adults. Error bars represent ± 1 standard deviation from the mean.

paring frequency differences at each level of the standard indicated that, although the difference between DLs for low- and high-frequency stimuli was largest at the lowest level, discrimination performance was significantly better for high- than for low-frequency increments at all three levels examined [frequency at 35 dB SPL, $F(1,18) = 30.79$, $p < .001$; at 45 dB SPL, $F(1,17) = 4.49$, $p < .05$; at 55 dB SPL, $F(1,19) = 19.23$, $p < .001$].

Because differential thresholds are limited by the absolute threshold of the standard, the performance of listeners characterized by differences in absolute threshold is more appropriately compared with level of the standard expressed in decibels SL rather than in SPL. In the present study, SLs for each age group were estimated from the group mean thresholds for 200-msec noise bursts presented in quiet, and the data are replotted as a function of these estimated SLs in Figure 2. The term *dB nHL* is used on the abscissa to denote that levels are referenced to group mean rather than to individual thresholds. With the data plotted in this fashion, it is clear that, as the level of the standard increased from approximately 10 to 30 dB nHL, improvements in discrimination performance were considerably larger for children than for adults. Separate two-way ANOVAs, including age (four levels) and level of the standard (three levels) as factors, confirmed that

the age $\times$ level interaction was significant for both low-frequency [$F(6,42) = 4.56$, $p < .01$] and high-frequency [$F(6,35) = 2.57$, $p < .05$] noise bands. Post hoc tests using Scheffé's multiple comparison procedure indicated that, for low-frequency noise, adult DLs decreased significantly from 1.9 to 1.2 dB ($p < .01$) as the level of the standard increased from 5 to 15 dB nHL but then remained constant at higher levels. For high-frequency noise, there were no significant differences in adult DLs for standards ranging from 12 to 42 dB nHL. Averaged across these four levels, mean adult DL was 0.8 dB. These values are in good agreement with level differences reported in the adult literature for similar types of stimuli (Miller, 1947; Viemeister, 1988). The absence of a significant effect of level for the high-frequency noise band may reflect the fact that no levels below 12 dB nHL were examined.

Comparable tests with children indicated that, as the level of the standard increased by 20 dB, the mean DLs of 1-year-olds decreased significantly from 6.7 to 3.0 dB ($p < .01$) for the low-frequency noise band and from 5.0 to 2.6 dB ($p < .01$) for the high-frequency noise band. The latter are nearly identical to the DLs reported by Schneider and Trehub (1985) for 12-month-olds' detection of increments in broadband noise at comparable levels of the standard. Equivalent DLs for 3-year-olds de-

Figure 2. Mean difference limens (ΔL) for 1-, 2-, and 3-year-old children and adults detecting 200-msec increments in continuous noise, plotted as a function of normal hearing level of the standard. Noise stimuli were two-octave bands centered at 400 and 4000 Hz. Error bars represent ± 1 standard deviation from the mean.

creased from 4.7 to 2.0 dB ($p < .01$) at low frequencies, and from 3.2 to 1.6 dB ($p < .05$) at high frequencies. These comparisons also revealed that improvements in performance were generally greatest between the two lower levels of the standard; DLs obtained for standards of approximately 20 and 30 dB nHL were not significantly different for any age group.

Additional post hoc comparisons across age groups indicated that intensity discrimination was significantly poorer in 1-year-olds than in both 2- and 3-year-old age groups at the two lower levels of the standard ($p < .01$), but not at the highest level. The performance of 1- and 2-year-olds was significantly poorer than adults' under all experimental conditions ($p < .05$), and 3-year-olds performed more poorly than adults for standards of 10 and 20 dB nHL ($p < .05$). However, when level of the standard was approximately 30 dB nHL, the DLs of 3-year-olds were not significantly different from those of adults for either low- or high-frequency noise bands.

DISCUSSION

At least two conclusions can be drawn from these results. First, the ability to detect increments in continuous noise improves significantly during early childhood, especially at low levels of the standard. At the highest level of the standard, approximately 30 dB nHL, children's performance approached that of adults by 3 years of age. This suggests a developmental time course more rapid

than that previously described in burst comparison studies. A consideration of levels employed in these experiments argues that the apparent difference in children's performance in the two paradigms is not due to differences in levels of the standard. Both Jensen and Neff (1993) and Faires and Lankford (1976) used standards of 70 dB SPL, 15 dB above the highest level used in the present study. Maxon and Hochberg (1982) examined burst comparison performance at several levels of the standard and found a progressive decrease in the DL for tones through at least 12 years of age for levels ranging from 10 to 60 dB SL. Clearly, the demands on memory and higher level cognitive processes are greater in burst comparison than in increment detection tasks. The finding of adultlike increment detection by 3 years of age is, therefore, consistent with Werner and Marean's (1996) view that much of the reported delay in maturation of intensity discrimination is due to nonsensory factors. However, differences in adult performance in the two paradigms have yet to be completely explained, and it is possible that immaturities in sensory mechanisms also contribute to the relatively slower rate of maturation reported in burst comparison studies.

For the age groups tested, the largest improvements in performance occurred between 1 and 2 years, with little additional improvement between 2 and 3 years of age. Since a slightly different experimental task was employed for 3-year-old listeners, it is possible that cognitive and motivational factors may have played a greater role in the

discrimination performance of this age group. We did find 3-year-olds more difficult to test than younger children, typically requiring extended periods of familiarization with the laboratory before agreeing to participate. Also, in several instances, 3-year-old children verbally reported the occurrence of increments but were either unable or unwilling to perform the appropriate motor response, suggesting that the task may have been too demanding for some 3-year-olds. However, since those children included in the final sample did respond appropriately and consistently by our criteria, the effect of task differences was probably minimal.

The second conclusion to be drawn from these data is that, for the experimental paradigm and range of stimuli used in the present study, there is no evidence of a frequency gradient in intensity discrimination by 1 year of age. Although DLs were significantly smaller for high- than for low-frequency noise bands with both children and adults, frequency-dependent differences did not vary across age groups. This finding is in contrast to results previously obtained for 7-month-old infants (Berg & Boswell, 1998), whose DLs at low levels of the standard were exceptionally large for low-frequency noise. Considered together, the results of the two studies suggest that there is a rapid improvement in the ability to detect increments in intensity at low frequencies during the latter half of the 1st year. The frequency gradient in absolute thresholds, however, appears to remain unchanged.

Perhaps the most striking aspect of the results is the large decrease seen in children's DLs with increasing level of the standard. As a general rule, the relationship between the DL and the level of the standard is described by Weber's law, which states that the just-detectable change in a stimulus is a constant proportion of its initial intensity. For standards ranging from near threshold to approximately 30 dB nHL, the results of adult listeners were generally consistent with Weber's law, whereas those of children were not. It might be argued that these different age trends result from the way in which sensation levels of the standards were estimated in the present study. Because nHLs were based on mean absolute thresholds obtained in a different group of listeners, low-level standards may have been below threshold for some children, resulting in unusually large DLs for these conditions. However, Maxon and Hochberg (1982) reported similar improvements in children's performance with increasing intensity, when SLs were determined in individual listeners. These findings suggest that developmental changes in intensity discrimination are most evident at low levels of the standard even when between-subjects differences in absolute threshold are not a factor. Given that such level effects are found in both increment detection and burst comparison paradigms, it seems likely that children's poorer discrimination performance at low intensities reflects immaturities in sensory, rather than nonsensory mechanisms.

The present results suggest that adultlike increment detection at low levels of the standard is not achieved until sometime after 3 years of age.

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NOTE

1. The use of a tracking algorithm in which changes in level were based only on outcomes on signal trials served to minimize the effect of false alarms on estimated threshold. Computer simulations indicated that an increase in false alarm rate from .10 to .18 would be expected to reduce the threshold Δ Ls of 1- and 2-year-old children by less than 0.5 dB. Adjusting obtained DLs for differences in mean false alarm rate did not alter the significance of the experimental effects.