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Development and the role of internal noise in detection and discrimination thresholds with narrow band stimuli

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Abstract

The experiments reported here examine the role of internal noise in the detection of a tone in narrow band noise and intensity discrimination for narrow band stimuli in school-aged children as compared to adults. Experiment 1 used 20-Hz wide bands of Gaussian and low-fluctuation noise centered at 500 Hz to assess the role of stimulus fluctuation in detection of a 500-Hz pure tone. Additional conditions tested whether performance was based on level and/or level-independent cues. Children's thresholds were elevated with respect to adults, and whereas adults benefited from the reduced fluctuation of low-fluctuation noise, children did not. Results from both groups were consistent with the use of a level cue. Experiment 2 estimated intensity increment thresholds for a narrow band Gaussian noise or a pure tone, either with or without a presentation-by-presentation level rove, an additional source of level variability. Stimulus variability was found to have a larger effect on performance of adults as compared to children, a rather counterintuitive finding if one thinks of children as more prone to informational masking introduced by stimulus variability. Both tone-in-noise and intensity discrimination data were consistent with the hypothesis that children's performance is limited by greater levels of internal noise.

I. INTRODUCTION

In many psychoacoustic paradigms, performance of young children is poor in comparison to the performance of adults. This has been found for relatively complex listening tasks, such as speech recognition under challenging listening conditions (e.g., Elliot, 1979; Nábelek and Robinson, 1982) and informational masking (Allen and Wightman, 1995; Hall *et al.*, 2005; Oh *et al.*, 2001; Wightman *et al.*, 2003). It has also been demonstrated for relatively simple tasks, such as the detection of a tone in quiet or in masking noise (Allen and Wightman, 1994; Fior, 1972; Maxon and Hochberg, 1982), frequency discrimination (Jensen and Neff, 1993; Maxon and Hochberg, 1982), and intensity discrimination (Fior, 1972; Maxon and Hochberg, 1982; see also Jensen and Neff, 1993). Although the time course of these developmental effects varies with paradigm and experimental conditions, there is at least some evidence of improvement out to 10–12 years of age in very simple psychoacoustic tasks (e.g., Maxon and Hochberg, 1982). A satisfactory explanation of these prolonged developmental effects for relatively simple psychoacoustic paradigms has proven elusive.

Previous research has considered a range of factors that might explain threshold elevation in children, including poor frequency selectivity, reduced motivation or inattention, and inefficient listening strategies. While any of these factors could contribute to the effects observed under some conditions, none seems to account for all effects observed. For example, Schneider *et al.* 1990 estimated critical bands and argued that the somewhat wider critical bands of infants and young children were not nearly wide enough to account for the elevation

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in masked thresholds observed. Motivation and inattention have been argued to be unlikely candidates based on relatively small effects of changing the task reward structure and the relative stability of thresholds over time for a given listener (for a review, see Schneider *et al.*, 1989). While listening strategy almost certainly plays a role in the performance of young children under some listening conditions, Willihnganz *et al.* 1997 provide evidence that it cannot account for all of the developmental effects observed, even under complex listening conditions. In that study, perceptual weights characterizing performance of adults and young school-aged children in a masked intensity discrimination paradigm were estimated; the pattern of weights did not suggest that children were using a particularly inefficient strategy when compared to adults, despite the finding of elevated thresholds for the younger listeners.

Schneider and colleagues (1989, 1992) suggest that increased internal noise might account for a wide range of developmental differences. While the phrase *internal noise* is sometimes used in a very broad sense, describing any of a number of inaccuracies that might account for deviations from optimal performance, the hypothesis proposed was more specific. In this case, internal noise was defined in terms of variability in the neural representation of intensity. Further, it was reasoned that increased internal noise would result in shallower psychometric functions in a masked detection task because energy at the output of the auditory filter centered on the signal would be more variable. Schneider *et al.* 1989 tested this hypothesis by estimating percent correct for the detection of a tone masked by a 1/3 octave band of noise; psychometric functions from group data failed to show compelling evidence that children's psychometric functions are shallower than those of adults. However, other studies (e.g., Allen and Wightman, 1994; Olsho *et al.*, 1988) have estimated psychometric functions based on *individual* listeners' data and have found an increase in slope with age, as would be expected if internal noise played a role in the elevated masked detection thresholds of the child listeners.

Internal noise has been very useful in helping to account for various psychoacoustical data of adult listeners, including intensity discrimination (Jesteadt *et al.*, 2003). Although the hypothesis that developmental differences in threshold sensitivity can be accounted for in terms of differences in internal noise is attractive, it has not been widely applied to studies of the developmental effects observed in simple psychoacoustic tasks. Our main purpose in the present study was to test the hypothesis that developmental effects observed with a simple psychoacoustic task in school-aged children can be explained, at least in part, in terms of internal noise.

One general strategy that has been used previously to study internal noise in adult listeners is to observe the effects of manipulating the variability of some physical parameter of the stimulus, such as intensity, and observing the effects on listener performance (Jesteadt *et al.*, 2003; Spiegel and Green, 1981). In this approach, the magnitude of change in performance due to changes in the variability of the physical parameter is used to draw inferences about the neural variability (or internal noise) associated with the detection process. One type of variability commonly introduced in psychophysical paradigms is that of level rove, whereby a random intensity is selected prior to each presentation interval from a restricted range (cf. Jesteadt *et al.*, 2003). Another source of variability is the within-interval fluctuation of a stimulus (Spiegel and Green, 1981), such as that characterizing random noise samples. Both experiments reported here use the general approach of assessing performance in the face of stimulus variability and making inferences about the magnitude of internal noise based on susceptibility to external noise.

Narrow band Gaussian noise is characterized by relatively prominent amplitude fluctuation dictated by its bandwidth, as well as the relative magnitudes and phases of the constituent components. In this context, the addition of a pure tone signal produces a number of effects that could potentially be used as detection cues: the overall level of the stimulus is increased, but there are also changes in envelope statistics, temporal fine-structure regularity, and, possibly, spectral shape. Level-independent cues can be shown to support the detection of a tone in bandpass Gaussian noise under conditions where level is an unreliable cue (Richards, 1992; Kidd *et al.*, 1989; Richards and Nekrich, 1993), such as in the presence of an intensity rove, and may be combined with a level cue under more typical (nonroved) conditions (Richards, 2001). The cues available for a tone in “low-fluctuation noise,” characterized by a relatively flat temporal envelope, are somewhat different from those available in Gaussian noise. Notably, adding a pure tone to a narrow band Gaussian noise tends to flatten the amplitude envelope of the stimulus, while adding a tone to a narrow band low-fluctuation noise can increase envelope fluctuation.

In adult listeners detection thresholds for a pure tone added to a low-fluctuation masker tend to be lower than those for a pure tone added to a comparable bandpass Gaussian noise masker (Hall *et al.*, 1998; Hartmann and Pumplin, 1988; Kohlrausch *et al.*, 1997; Eddins and Barber, 1998; but also see Eddins, 2001). At least two possibilities have been suggested to account for this finding. Kohlrausch *et al.* 1997 suggested that the change in envelope statistics with the addition of a tonal signal is responsible. Eddins (2001) offered an alternative suggestion that the short-term stability of low-fluctuation noise maskers facilitate the detection of an increment in intensity. This interpretation was supported by data on intensity discrimination; thresholds for low-fluctuation noise were lower than those for Gaussian noise, even when the signal interval was associated with a change in level and no change in the envelope statistics. This interpretation is also consistent with the views of Bos and deBoer (1966), who argued that both intensity discrimination and masked tone detection are limited at narrow bandwidths (10–40 Hz) by inherent stimulus fluctuations.

As mentioned at the outset, intensity discrimination has been shown in some studies to be elevated in school-aged children. Thus, children might be poorer than adults in detecting a signal in noise because of relatively poor ability to utilize the associated level cue. It is less clear how well children make use of level-invariant cues for a tone added to narrow band noise. Allen *et al.* 1998 examined the types of cues used by children in a tone-in-noise detection task for a 400-Hz wide masker centered at 1 kHz. Preschool aged children were able to use level-invariant cues, such as temporal changes in the masker with the addition of a signal. It was also noted that at the detection threshold of children, multiple cues associated with the signal would be present in the physical stimulus: it was hypothesized that children may not be good at integrating the different cues available or switching between cues.

Very little is known about the effect of stimulus variability on young school-aged children in tone detection or intensity discrimination with narrow band stimuli other than tones. Preliminary data collected in our lab in the course of a binaural experiment, however, suggested that children 5–9 years of age might perform quite differently from adults in the face of stimulus variability. In that study (Buss *et al.*, 2003), diotic thresholds for a 500-Hz tone in a 20-Hz wide narrow band of noise centered on 500 Hz were measured for both Gaussian and low-fluctuation noise. While adults showed the expected masker effect, with lower thresholds in low-fluctuation noise, children had very similar thresholds in low-fluctuation and Gaussian noise, suggesting that they may not be able to take advantage of the cues available in low-fluctuation noise. Experiment 1 pursued this preliminary finding by estimating monaural pure-tone detection thresholds in both Gaussian noise and low-fluctuation noise. Additional conditions measured sensitivity to either level cues or level-independent cues present in the tone-in-noise task in order to confirm that any age effects obtained with a tone in noise were related to level (and not level-independent) cues. Experiment 2 used stimuli with high or low degrees of inherent fluctuation and examined the effects of additional variability introduced by level rove on intensity discrimination, a paradigm closely resembling that used in adults by Jesteadt *et al.* 2003 to estimate internal noise.

II. EXPERIMENT 1: ENVELOPE FLUCTUATION AND MONAURAL CUES FOR MASKED TONE DETECTION

The purpose of Experiment 1 was to test the prediction that if internal noise is the limiting factor in children's detection of a tone in narrow band noise, then they should not benefit from reduced masker fluctuation to the same extent as adults, for whom external noise plays more of a role in performance. In other words, elevated levels of internal noise could result in a failure of children to make effective use of the more stable level cues in low-fluctuation as compared to Gaussian noise. Because this logic rests on the assumption that listeners are using a level cue to perform the task, and because multiple cues are available for these stimulus conditions, additional conditions were run in which level and level-independent cues were assessed separately. Results of these additional conditions will be interpreted in terms of the cues most likely to underlie performance in the tone-in-noise conditions. Further, if children have difficulties integrating multiple cues in the basic conditions, as suggested by the results of Allen *et al.* 1998, then these blocks of stimuli characterized by reduced cues (e.g., just level) should give a more accurate indication of the child listeners' abilities to make use of level and level-independent cues.

A. Methods

1. Listeners—A group of 8 children participated, including 6 males and 2 females, aged 5.0 to 10.5 yr (mean=7.3 yr). The adult group was comprised of 10 listeners, 2 males and 8 females, aged 18.0 to 48.0 yr (mean=28.4 yr). All listeners had pure tone thresholds equal to or better than 15 dB HL for octave frequencies 250 to 8000 Hz (ANSI, 1996). None of the listeners reported a history of ear problems. A history of ear disease, including chronic otitis media (OM), or an active case of OM at the time of testing were considered grounds for exclusion from the study. Data for one additional 7-years-old child listener were excluded from the study due to excessive variability in performance. Thresholds for this child varied by more than 25 dB in one condition in a single session: this variability was attributed to fatigue and inattention rather than to learning because thresholds increased (worsened) over the course of the session.

2. Stimuli—The Gaussian masker was a 20-Hz wide band of noise centered on 500 Hz. The low-fluctuation noise was generated following a procedure described by Kohlrausch *et al.* 1997. First, a 20-Hz wide band of Gaussian noise centered on 500 Hz was generated; the sample was divided by its Hilbert envelope in the time domain and then restricted to the original 20-Hz spectral region via multiplication in the frequency domain, a procedure that was repeated 10 times for each sample. This process resulted in a masker with a relatively flat temporal envelope. Quantifying envelope fluctuation as the ratio between the standard deviation and the mean of the envelope (V), the low-fluctuation and Gaussian noise maskers are characterized by V=−24.1 and V=−5.6 dB, respectively. In terms of the modulation depth (m) for sinusoidal amplitude modulation, these values are comparable to m=0.09 and m=0.74, respectively (see Kohlrausch *et al.*, 1997). Maskers were scaled to a digital amplitude associated with 65 dB SPL and presented for 409-ms, including 50-ms $\cos^2$ ramps. The signal was a 500-Hz pure tone, 309 ms in duration. When present, the signal was ramped on and off using 50-ms $\cos^2$ ramps, with onset occurring 100-ms after onset of the masker, and the signal level was adjusted by way of a scalar. Stimuli were generated digitally in MATLAB and played out via two channels of a DAC (TDT, RP2) at approximately 12.2 kHz. The resultant streams were routed through a headphone buffer (TDT, HB7) to the left earphone of a pair of circumaural earphones (Sennheiser, HD 265).

Maskers were generated using arrays of 2^{13} points. The effect of truncating these arrays to the number of points associated with 409 ms (4993 points) and imposing ramps introduced some variability around the 65-dB mean masker level. This effect was estimated based on 100 samples, generated following the procedures described above, with the level for each sample calculated based on the steady portion of the stimulus (i.e., excluding ramps). For Gaussian noise stimuli, 50% of the samples were within ±0.5 dB of 65 dB SPL, 75% were within ±1 dB, and 90% were within ±1.5 dB. For low-fluctuation noise stimuli, 90% of the samples were within ±0.5 dB of 65 dB SPL. The effects of this source of stimulus variability will be revisited below.

For the purposes of stimulus generation, the 409-ms masker was divided into two portions: the *fringe* and the *core*. The *fringe* portion of the masker was 150-ms in duration, including 50-ms $\cos^2$ onset and offset ramps. The *core* portion of the masker received the same gating as the pure tone signal: that is, it was 309-ms in duration, including 50-ms $\cos^2$ ramps. The *fringe* offset and the *core* onset masker ramps overlapped in time, such that the masker sounded continuous when the two portions were played together. Dividing the masker in this way allowed the independent manipulation of the *core* portion of the masker in conditions where cues were limited to either just level or just envelope. The primary motivation for the use of a masker fringe was to allow comparison with tone-in-noise data collected using an asynchronous onset. The implications for adopting the *core*/*fringe* stimulus configuration in the present study are considered further in the discussion section.

In the *all-cues* condition, the 500-Hz pure-tone signal was simply added to the masker with no further adjustment made to the *core* portion of the masker. This condition is referred to as the *all-cues* condition because the addition of the signal introduces both level and level-independent cues. In a second condition, the signal was an increment in intensity of the *core* portion of the masker. In this case, waveform amplitude of the *core* portion of the masker was adjusted according to the increment that *would have been obtained* by the addition of a pure tone signal at the associated signal level. This was computed with the formula $10 \log(10^{65/10} + 10^{\mathrm{Sig\ Lev}/10})$, where Sig/Lev is the level of the simulated pure-tone signal, in dB. As such, thresholds in this condition can be directly compared to those obtained in the *all-cues* condition. This condition is referred to as the *level-only* condition because the signal consists of an increment in the level in the core portion of the masker and is not associated with level-independent cues, such as a change in envelope statistics within that portion of the masker. In the final condition, a pure tone signal was added to the masker, but the sum (signal+core) was scaled down to counteract any resultant change in level. In this *no-level* condition there was a change in the stimulus envelope with the addition of the signal, but no change in the overall level. Other possible cues in the *no-level* condition include the regularity of zero-crossings and spectral shape, although the latter was unlikely to be a viable detection cue for such a narrow bandwidth.

Maximum values for *no-level* tracks were imposed because of the nonmonotonicity of some of the temporal stimulus features thought to provide possible cues. For example, the temporal envelope of a low-fluctuation noise masker alone is relatively flat. With the addition of a tone, envelope variability increases with increases in signal level up to a point, but beyond that point variability begins to drop, as the stimulus envelope becomes dominated by the pure-tone signal. Based on these considerations, and calculations of possible level-invariant cues (i.e., average envelope slope, envelope max/min ratio, and periodicity of zero crossings), it was decided to impose a track ceiling value of 65 dB SPL for low-fluctuation noise, the approximate signal level associated with the most prominent level-invariant cues. A ceiling of 90 dB SPL was set for the *no-level* Gaussian noise masker stimuli; while level-invariant cues were monotonic for this masker type, it was reasoned that failure to make use of these cues with a 90 dB signal would not likely change in the face of further increases in signal strength. A threshold estimate was judged to be at ceiling if the threshold estimation track hit ceiling three or more times during a run, and an average data point for a given condition was judged to be unmeasurable if two or more threshold estimates were at ceiling.

To summarize, there were six conditions in total, illustrated in Fig. 1. In this figure, an example Gaussian noise sample is shown in the left panel and an example low-fluctuation noise sample in the right. The repeated gray waveform is the masker alone and the associated black lines indicate the envelope of a signal-plus-masker, with both signal and masker presented at a level of 65 dB SPL. At the top of each panel are indications of the temporal placement (and overlap) of the *fringe* and *core* portions of the stimuli. In the *all-cues* condition the signal was a pure tone gated with the ramps defining the *core* portion of the stimulus; interactions between signal and masker produced both level and envelope cues. In the *level-only* conditions the signal consists of an increment in masker level, defined as the increment that would have been produced if a pure tone signal had been added. In these conditions there was no change in envelope statistics over the course of the signal presentation to cue the presence of the signal other than those at the boundary of the *fringe* and *core* segments. In the *no-level* conditions the overall level of the *core* portion of the stimulus was scaled back after addition of the signal such that a change in envelope statistics over the course of the signal presentation cued the presence of the signal, but there was no increase in level.

3. Procedures—Threshold estimates were obtained using a 3-alternative forced-choice procedure and a 3-down 1-up tracking rule, estimating 79% correct on the psychometric function (Levitt, 1971). Initial signal level adjustments were made in steps of 4 dB, and level adjustments were reduced to 2 dB after the second track reversal. Each track continued for a total of six reversals, and the final threshold estimate was the mean level at the last four reversals. Listening intervals were marked visually via animation on a computer screen. Over the course of a track a cartoon picture was unmasked, in the style of a jigsaw puzzle, with one piece revealed following each correct response. No visual feedback was provided, following an incorrect response. At the end of the track the cartoon was fully revealed and performed a two-second animation. All listeners used this interface.

On the first visit to the lab, child listeners were randomly assigned to one of two groups. One group ran a block of the *all-cues* and a block of the *level-only* condition for each masker type. The other group ran a block of the *all-cues* and a block of the *no-level* condition for each masker type. On the second visit to the lab, child listeners performed a second block of the *all-cues* condition and a block of the reduced-cue condition they had not previously listened to (either *level-only* or *no-level*) for each masker type. Within a visit, the order of the four blocks (2 signal conditions×2 masker types) was randomized. Adult listeners followed the same sequence of blocks, but were able to complete more than four blocks in a visit. Each visit lasted no longer than one hour, with frequent breaks. A block of trials consisted of three threshold estimates, with a fourth if the span in initial estimates was 3 dB or more. All estimates for a listener were averaged to produce the final thresholds reported below.

Prior to each block, the experimenter described the detection cue associated with that condition. For the *level-only* condition, listeners were asked to select the loudest interval. In the *no-level* condition, the signal was described as the "more wobbly" sound for low-fluctuation noise and the "smoother, or less wobbly" sound for Gaussian noise. In the *all-cues* condition, instructions were to listen to loudness and/or degree of fluctuation. In all cases, use of visual feedback to optimize performance was encouraged.

B. Results

The *all-cues* condition was performed twice by each listener for each masker type. This was done in part to assess the stability of this very important baseline condition. To that end the first and the second replicate thresholds were compared for evidence of improvement.[1] One-

[1]Due to time constraints, one child listener did not repeat the *all-cues* condition, so his data are not represented in this analysis.

tailed, paired *t* tests revealed no improvement between the first and second replication for Gaussian (t_{16}=−1.16, p=0.13) or low-fluctuation noise (t_{16}=0.90, p =0.19). Tests with just child and just adult data similarly resulted in no significant difference between the first and second block of thresholds (α =0.05). Subsequent analyses incorporating *all-cues* data were performed based on the first set of estimates obtained, although results are qualitatively identical when analyses are performed on the mean of all (six to eight) threshold estimates in the *all-cues* condition.

Figure 2 shows the mean thresholds for each group (bars) and individual listeners' thresholds (circles) obtained with Gaussian noise (top) and low-fluctuation noise (bottom). Individuals' thresholds are ordered by listener age, youngest (left) to oldest (right) within group. Open bars and open circles indicate adult data, and hatched bars and filled circles indicate child data. In the *all-cues* condition, mean thresholds for adults were 68.2 and 62.5 dB SPL for Gaussian and low-fluctuation noise, respectively. This difference of 5.7 dB was significantly greater than zero in a paired *t* test (t_9 =5.09, p < 0.001, two-tailed). This result is comparable to the 5-dB effect reported by Hall *et al.* 1998 for 10-Hz wide noise bands centered at 500 Hz. In contrast, for children the mean thresholds were 69.9 and 70.4 dB in Gaussian and low-fluctuation noise. The masker effect of only 0.5 dB was not significant (t_7 =0.105, p=0.92, two-tailed). This result closely replicates results for analogous diotic stimuli collected in the course of a binaural study (Buss *et al.*, 2003).[2] The +5 dB S/N ratio at threshold for the Gaussian noise masker can be compared with the results of Hall *et al.* 1997. In one condition of that study, thresholds were estimated for the detection of a 500-Hz pure tone masked by a 20-Hz wide band of noise centered on 500 Hz. The masker was 600 ms in duration, and the signal was 400 ms, with signal onset occurring 200 ms after masker onset. The average threshold for school-aged listeners in that study (ranging from 5–11 yrs) was +3.4 dB S/N, comparable to the +5 dB S/N observed here.

The second set of bars in each panel of Fig. 2 shows thresholds in the *level-only* condition. In all cases these thresholds are quite similar to those in the corresponding *all-cues* condition. A repeated-measures ANOVA was performed to assess this relationship. There was one between-subjects factor (AGE: child, adult) and two within-subject factors (CUE: *all-cues*, *level-only*; MASKER: Gaussian, low-fluctuation). There was a significant main effect of AGE ($F_{1,16}$=16.23, p<0.001) and a significant main effect of MASKER ($F_{1,16}$=40.42, p<0.0005). The interaction between AGE and MASKER was significant ($F_{1,16}$=27.77, p < 0.0005). There was no main effect of CUE ($F_{1,16}$=1.56, p=0.23) and no interactions between CUE and the other factors. This confirms that the *level-only* and *all-cues* thresholds were not statistically different. Thus, there was a significant masker effect in the *level-only* condition for adults, but no significant effect for children.

The right-most set of bars in each panel of Fig. 2 shows results of the *no-level* condition. Only those data points deemed to be measurable were included in the average, so these results tend to underestimate thresholds by way of excluding large values at ceiling. The proportion of data points included in each mean is indicated at the base of each bar or in place of a bar. For the Gaussian noise masker, none of the children obtained a threshold below the ceiling value of 90 dB SPL. All but one of the adults performed below the ceiling, but thresholds in this condition were elevated more than 10 dB relative to the *all-cues* condition. These results suggest that cues other than level (e.g., envelope) probably played little or no role in performance in the *all-cues* condition with Gaussian noise. For low-fluctuation noise, 3/8 of children and 8/10 of adults produced a threshold estimate below the ceiling of 65 dB SPL. In all cases where a measurable threshold was obtained, the resultant threshold was near 62 dB, similar to average adult *all-cue* threshold and 8 dB better than average child *all-cue* threshold.

[2] Buss *et al.* 2003 ran 13 child listeners, two of whom also participated in Experiment 1.

The three children who performed below ceiling in the *no-level* condition attained thresholds approximately 5 dB lower than their thresholds in the associated *all-cue* condition. This suggests that these listeners failed to make use of level-independent cues present in the *all-cue* condition.

C. Discussion

Experiment 1 showed that adults were more sensitive at detecting a tone added to a low-fluctuation masker as compared to a Gaussian noise masker, and children showed no such masker effect. While children's detection thresholds did not vary as a function of masker type, it seems reasonable to assume that children were able to perceive a difference between Gaussian and low-fluctuation noise stimuli. A 20-Hz wide band of Gaussian noise has an equivalent AM rate of approximately 13 Hz (Rice, 1953). Based on the temporal modulation transfer function (TMTF) data of Hall and Grose (1994), at a modulation rate of near 13 Hz, AM of the Gaussian noise (with m=0.74) should be clearly perceptible for all child listeners, while modulation for the low-fluctuation stimuli (with m=0.09) would be expected to fall below the modulation detection threshold. This suggests that child listeners in Experiment 1 should be able to perceive the difference between the envelope fluctuation of Gaussian and low-fluctuation noise, and yet these perceptible differences did not affect the performance. There are no published AM discrimination data that permit the assessment of the relative sensitivity to AM in children and adults, another factor that could bear on the absence of a masker effect in the current dataset.

It is possible that children might have particularly elevated thresholds for a tone masked by a low-fluctuation noise when compared to adults because of increased cue complexity. If the cues allowing adults to achieve lower thresholds with low-fluctuation noise are more subtle or complex than those present in the Gaussian noise case, and if children are not as adept as adults at combining or switching between cues available in low-fluctuation noise, then low-fluctuation noise thresholds in children would not benefit from these additional subtle or complex cues. This hypothesis is similar to that proposed by Allen *et al.* 1998 to account for tone-in-noise masking results obtained with preschool-aged children. The fact that 3 out of 8 child listeners attained lower thresholds in the *no-level* than the *all-cues* conditions is consistent with this view.

Results of the reduced-cue conditions suggest that an increment in level may be the primary cue underlying thresholds for a tone added to a narrow band of noise for most listeners, both children and adults. Level-invariant cues in isolation were associated with elevated or unmeasureable thresholds for the Gaussian noise masker, and so almost certainly played no material role in detection for the *all-cues* Gaussian condition. The level-invariant cues associated with the low-fluctuation masker support a relatively good performance for some adult listeners, comparable to that seen in the *all-cues* condition. The failure of many listeners to attain a threshold below the ceiling value of 65 dB SPL, however, suggests that this cue is not viable for all adult listeners and fewer than half of the child listeners. These observations are consistent with the conclusion that performance in the *all-cues* condition can be most parsimoniously explained in terms of the change in level across intervals associate with the addition of a signal. This does not imply that child observers are not able to make use of level-invariant cues, in general. Indeed, Allen *et al.* 1998 showed that preschool listeners are able to make use of level-invariant cues in the detection of a tone in bandpass noise spanning 800–1200 Hz. The assertion is just that the *present* results are likely based on level.

One aspect of the current paradigm that varies from the one employed by Allen *et al.* 1998 is the use of a leading *fringe*. It has been shown that asynchronous onset can aid in sound source segregation (Bregman, 1990), and that school-aged children can make use of gating cues in an informational masking paradigm (Hall *et al.*, 2005). Based on these findings it is plausible that delaying the onset of the signal portion of the stimulus could have the benefit of improving signal detection by virtue of improved segregation. A second factor of interest is the role of memory in this paradigm. The presence of a fringe prior to signal presentation offers the opportunity for the subject to make a within-interval comparison of the *fringe* and *core* segments of the stimulus. Because no across-interval comparison is necessary for this strategy, the availability of such a cue could improve the performance of child listeners. Alternatively, asynchronous onset could introduce added complexity and make the task more difficult for child listeners just by virtue of increasing the number and quick succession of different stimulus features. This is unlikely in light of the results of Hall *et al.* 1997, however. That study measured thresholds for school-aged and adult listeners for stimuli comparable to those in the *all-cues* condition. No difference was observed between a condition in which a narrow band masker was played continuously and a gated condition, where the masker was gated on 200 ms prior to the signal and both the signal and masker were gated off synchronously. This result argues against the idea that increased task complexity associated with the fringe could have elevated thresholds in the present study, at least for Gaussian noise conditions. One motivation for Experiment 2 was to test the fidelity with which level cues can be used under conditions of synchronous onset to determine whether the results of Experiment 1 would generalize to other stimulus conditions.

One interesting result of Experiment 1 is the significant MASKER × AGE interaction in the *level-only* condition. As in the *all-cues* condition, thresholds in the *level-only* condition varied across masker for adults but not for children: adults' thresholds in the *level-only* condition were 4.1 dB lower for low-fluctuation than Gaussian noise, while for children the difference was a (nonsignificant) 1.0 dB. The advantage for intensity discrimination in low-fluctuation as compared to Gaussian noise obtained for adults was noted by Eddins (2001). In that study adults discriminated level across interval for 50-Hz wide bands of noise, and average thresholds were 3.2 dB lower for low noise than Gaussian noise. Eddins speculated that the reason for the different intensity discrimination thresholds across stimulus types was the stability of the short-term level cue. However, if the performance of children is limited by internal noise rather than external noise, as hypothesized in the Introduction, then children would not be able to benefit from this reduction in external noise. Results of Experiment 1 provide preliminary support for this hypothesis.

III. EXPERIMENT 2: THE EFFECT OF STIMULUS VARIABILITY ON INTENSITY DISCRIMINATION

Whereas the paradigm of Experiment 1 examined the effects of inherent stimulus fluctuation on the use of level cues in adults and children, Experiment 2 incorporates level rove as an additional source of stimulus variability. Roving the level of the stimuli on an interval-by-interval basis introduces external noise that would be expected to elevate thresholds to the extent that external noise (as opposed to internal noise) imposes limits on performance. Similar to the approach taken in Experiment 1, the hypothesis of Experiment 2 is that children's intensity discrimination thresholds should be less severely elevated by level rove than those of adults. This result would be expected if the performance of children is limited by internal noise to a greater extent than that of adults.

To that end, Experiment 2 addresses the role of both within-interval and across-interval stimulus variability in intensity discrimination of adults and children. Thresholds for detecting an across-interval increment in intensity were estimated for a narrow band Gaussian masker and for a pure tone, characterized by pronounced variability and very steady within-interval intensity, respectively. An additional manipulation imposed a random level rove to each stimulus presentation, which has the consequence of increasing the variability of the intensity cue.

A. Methods

1. Listeners—A group of 15 children participated, including 10 males and 5 females, ages 5.0 to 10.5 yr (mean=7.9 yr). The adult group was comprised of 12 listeners, 3 males and 9 females, ages 17.1 to 50.0 yr (mean=29.2 yr). Exclusion criteria and audiometric status were the same as those described for Experiment 1. Two additional child listeners (5 and 7 yr) were excused due to excessive variability in threshold estimates; these listeners consistently provided a 10+ dB spread in thresholds within condition. Two of the child listeners and two of the adult listeners had previously participated in Experiment 1.

2. Stimuli—Stimulus generation was similar to that described for Experiment 1. Stimuli were either 20-Hz wide bands of Gaussian noise centered on 500-Hz or 500-Hz pure tones, ramped on and off with 50-ms $\cos^2$ ramps and 409-ms in duration (including ramps). Noise samples were generated in the time domain, converted to the frequency domain for filtering by way of multiplication with a boxcar function, converted to the time domain, truncated to 409 ms and ramped with 50-ms $\cos^2$ functions. Pure tones were generated in the time domain, truncated and ramped. Like the *level-only* condition of Experiment 1, the standard interval stimulus was 65 dB SPL and the signal was an increment in the level, produced by adding a scaled copy of the standard. In contrast to Experiment 1, such increments spanned the entire (409-ms) stimulus duration. In an additional manipulation, the standard presented in each interval was roved in level, according to a random draw from a uniform distribution ±6 dB. The level of the "scaled copy" (producing the level increment in the signal interval) was not roved in these conditions.

The condition in which the tonal standard was roved in level will be referred to as a *tone roved*, and the condition with no rove will be referred to as the *tone-steady* condition. Analogous conditions with Gaussian noise stimuli will be referred to as *Gnoiseroved* and *Gnoise-steady*, respectively.

3. Procedures—As in Experiment 1, listeners performed a 3-alternative forced-choice track with visual indications of the listening intervals and positive feedback following a correct response. Instructions were to select the loudest of the three intervals. The signal level was adjusted in a 3-down, 1-up procedure, with 4 dB steps at the outset and 2 dB after the first 2 reversals. As above, thresholds are reported *as if* the signal was added to the masker in random phase, to facilitate comparison of these results with the tone-in-noise results of Experiment 1. The four conditions were run in blocks, with blocks visited in random order. Three threshold estimates were obtained in each block, with a fourth collected in cases when the initial three spanned a range of 3 dB or more. Listening sessions lasted no more than 1 hour, with frequent breaks. In most cases child listeners were able to complete all four conditions in this time period, although in several cases more than one test session was required. All adult listeners completed the study in a single 1 h session.

Thresholds in this experiment were highly variable, particularly in the child group. Effects of this variability were counteracted by the following procedure for identifying outliers. The difference between the maximum and the minimum threshold in a block of estimates was computed. If that value was 6 dB or greater, the set was visually examined for outliers, defined as a single threshold estimate that is at least 4 dB greater than or less than all the other estimates in that condition. If an outlier was identified, it was removed from the mean. Following this procedure, fewer than 5% of the child data and 2.5% of the adult data were culled from the results presented below.[3]

[3]Elimination of these data points did not change the general conclusions of the experiment. Repeating the statistics with outlier data included produced the same pattern of significance as reported in Sec. III B.

B. Results

Thresholds for each listener in each condition are indicated with open circles in Fig. 3, with data for adults in the left panel and those for children in the right panel. The labels on the abscissa indicate the associated stimulus condition. The left ordinate indicates signal level at threshold in dB and the right ordinate shows associated units of ΔL, to facilitate a comparison with published intensity discrimination data. Average thresholds in the *Gnoise-steady* condition are 65.8 dB for adults and 68.9 for children. These values are within 2.5 dB of those observed in comparable conditions in Experiment 1. The inclusion of stimulus rove increased these thresholds by 3.7 for adults and by 3.1 dB for children. Average thresholds in the *tone-steady* condition are 61.5 for adults and 66.7 for children. The inclusion of rove increased these thresholds by 7.0 and 4.0 dB for the adults and children, respectively. Thus, the effect of rove was larger for the pure tone than for the noise stimulus, and the effect of rove for the pure-tone stimulus was larger for adults than for children. Comparing *tone-steady* and *Gnoise-steady* conditions, the effect of stimulus type was 4.3 dB for adults and 2.2 dB for children. Thus, increases in threshold associated with introduction of stimulus variability, either rove or inherent (within interval) fluctuation, were larger for adults than children when using the *tone-steady* condition as a baseline.

A repeated-measures ANOVA was performed on data in units of dB[4] to assess the significance of these effects. There was one between-subjects factor (AGE: adult, child) and two within-subject factors (ROVE: steady, roved; STIM: Gaussian noise, tone). There were significant main effects of AGE ($F_{1,25}$=24.97, $p < 0.0001$), ROVE ($F_{1,25}$=187.98, $p < 0.0001$) and STIM ($F_{1,25}$=53.88, $p < 0.0001$). The two-way interaction between ROVE and STIM was significant ($F_{1,25}$=19.93, $p < 0.001$), reflecting a larger effect of rove for the tone as compared to Gaussian noise. The ROVE×AGE effect ($F_{1,25}$=7.89, $p < 0.01$) reflects greater susceptibility to the rove of adults as compared to children. The STIM ×AGE interaction failed to reach significance ($F_{1,25}$ =2.14,p=0.16). The significant three-way interaction ($F_{1,25}$ =6.12,p<0.05) is consistent with the observation that the largest rove effect is associated with the *tone-steady* data of adults.

Comparing the results of the *all-cues* condition of Experiment 1 to those of the no-rove conditions of Experiment 2 indicates analogous effects of stimulus fluctuation. In Experiment 1, thresholds of adult listeners dropped (improved) by 5.7 dB, comparing Gaussian with low-fluctuation noise conditions. In Experiment 2 a drop of 4.3 dB is observed comparing the *Gnoise-steady* and *tone-steady* conditions. For child listeners, improvements in threshold were smaller than those observed in adults, with values of 0.5 and 2.3 dB, respectively. These results suggest that the *fringe/core* stimulus configuration of Experiment 1 was not of great consequence to the interaction between age and effects of stimulus fluctuation.

C. Discussion

The results of Experiment 2 suggest that stimulus variability had less of an effect on the results of child than adult listeners, consistent with the hypothesis that child listeners are operating under conditions of elevated internal noise. One relatively uninteresting source of error in child listeners' performance is confusion regarding the signal cue. As noted by Jesteadt *et al.* 2003, feedback can often be misleading in roved intensity discrimination. Under such conditions the stimulus in the "signal" interval can, in fact, be the least intense; this occurs when the "signal" interval is associated with a low value of rove and/or the "no-signal" intervals are associated with a high value of rove. It is plausible that children could be more prone to

[4]The primary consideration in selection of units for intensity discrimination, apart from ease of comparison with other data, was compliance with assumptions regarding the variance across the dataset. For the ANOVA, Box's Test of equality of covariance was not significant (p=0.10) for data represented in dB SPL. Units of ΔL were less consistent with assumptions of normal and uniform variance: in that case Box's Test was significant ($p < 0.05$), indicating that the covariance matrices were not equal across groups. This result motivated the use of dB SPL units in the statistical tests reported here.

confusion in the face of spurious feedback than adults. There are several considerations suggesting that this probably did not play a substantial role in the results obtained here, however. First, both adults and children performed the experiment using an interface where correct responses were rewarded by the unmasking of one piece of a "puzzle." Following an incorrect response there was no such unmasking. Listeners were not informed explicitly about this reward structure, and it seems likely that positive feedback (unmasking of a piece) would be more salient than negative feedback (nothing happening). As such, the listener would not receive salient feedback that an unselected and less intense stimulus was in fact the signal. Second, if spurious feedback causes more confusion in children than adults, then one might expect to see a larger effect of rove for children than adults. In fact, the opposite result was observed, with child listeners' data more closely resembling that of adults in the roved conditions. Finally, there is a good correspondence in the pattern of results obtained in Experiments 1 and 2. In Experiment 1, external variability was manipulated by way of stimuli with large and small fluctuations over time, but no interval-by-interval rove (and hence no spurious feedback). As such, the most parsimonious explanation of the results of Experiment 2 would not rely on confusion associated with rove. If the elevated thresholds of the child listeners are due to some factor that is not specific to the current paradigm, then, the challenge is how to characterize that error and identify its source.

One way to summarize the findings of Experiment 2 is to note that the largest effect of stimulus variability is observed in cases where the baseline sensitivity was quite good (e.g., adult, *tone-steady* data). This observation prompted an attempt to model these results in terms of the combined effects of internal and external noise. In classic treatments of internal noise, sensitivity (d') is defined in terms of the mean difference in signal and no-signal cues (Δ) divided by the standard deviation of those underlying cue distributions (σ). The value of σ can be decomposed into internal noise (σ_i) and external noise (σ_e), resulting in the equation

$$d' = \Delta \Big/ \sqrt{(\sigma_e^2 + \sigma_i^2)}. \quad (1)$$

Jesteadt *et al.* 2003 provide a modern treatment of this classical approach. While there is some debate regarding the appropriate units in which to perform these calculations, following Jesteadt *et al.*, calculations reported here were performed in units of ΔL, and internal and external variability was assumed to add in dB.

The 3-down 1-up tracking procedure used in Experiment 2 estimates 79% correct, associated with a d' of 1.61 for a 3-alternative forced-choice task. Assuming that thresholds in the *tone-steady* condition are dominated by internal noise (i.e., $\sigma_e \approx 0$), the value of internal noise can be estimated as $\sigma_i = \Delta/1.61$. For adults' mean data, this produces an estimate of internal noise of σ_i =0.99 comparable to that reported for the adult listeners of Jesteadt *et al.* 2003. For children, the estimate of internal noise was considerably larger, with σ_i =2.46.

For the remaining stimulus conditions, external noise is greater than zero, due to rove and/or small differences in level that arose because stimuli were equalized based on a longer sample than the one presented. Procedures for estimating thresholds based on these sources of variability are discussed in Appendix A. Predicted values of ΔL appear as dark lines in Fig. 3. These estimates capture the general trends in the data, most notably the biggest effects of external noise seen when comparing adult *tone-steady* to *tone-roved* conditions. Predicted thresholds in the *tone-steady* condition are quite close to the mean observed thresholds in each group; this is a consequence of the fact that values of σ_i were fitted based on these thresholds. Predicted thresholds in other conditions tend to underpredict performance by 1.4–2.4 dB. In adult data, predicted thresholds fall 3+ standard errors of the mean below the mean in all three conditions characterized by high external noise. A similar pattern is observed in the data of child listeners, with the caveat that increased variance across individuals, reduces the magnitude of differences relative to estimates of the standard error. The underprediction of thresholds in cases of elevated values of σ_e is consistent with the findings of Eddins (2001), who showed that intensity discrimination is impaired for fluctuating (Gaussian noise) as compared to relatively stable (low-fluctuation noise) stimuli, even though overall stimulus level was stable in both cases. The fact that both rove and inherent fluctuation are associated with higher-than-expected thresholds in the current dataset suggests that these results are probably not due to the effects of amplitude modulation on loudness (e.g., Zhang and Zeng, 1997). Regardless of the source, this effect is roughly comparable in adult and child listeners' data, with an average mismatch of 1.7 and 1.9 dB between the prediction and mean threshold, respectively.

These discrepancies aside, the results shown in Fig. 3 suggest that the differential effects of stimulus variability across subject groups are broadly consistent with a very simple model of the combination of internal and external noise. By this account, children are less susceptible to the effects of stimulus variability because their rather large internal noise has a dominant effect on the internal representation of the cue. Similar logic can be used to account (at least in part) for the pattern of results obtained in the *all-cues and level-only* conditions of Experiment 1. In these data, adults' thresholds were more affected by the degree of inherent masker fluctuation (Gaussian versus low-fluctuation noise) than were the children's thresholds. This result is consistent with the argument that the lower levels of internal noise of adults make them more susceptible to the disruptive effects of external noise (i.e., stimulus variability).

While this approach is reasonably successful in characterizing the general trends in processing errors of child as compared to adult observers, it does not identify the source of that error. The foundation of the approach taken here (and in Jesteadt *et al.*, 2003) rests on the assumption that the source of noise reflects the physiological limitations associated with the encoding of the cues underlying performance. Self-generated noise, such as that produced by breathing or shifting position, could introduce noise that is not specific to the auditory system and might well be better characterized as "external" from the point of view of auditory processing. Further, the model proposed here assumes that the cues underlying performance are submitted to an optimal detector to generate a response, a process that is well characterized by signal detection theory. Evidence that children behave according to the rules of signal detection theory is scant, however. In the classic model, for example, the psychometric function has a well-defined shape determined by the internal noise distribution. It is possible that child listeners may change strategy or lose motivation under conditions of increased task difficulty, rather than consistently following a well-specified strategy, a result that could be reflected in an oddly shaped psychometric function. If the expectations of the classic model are met, however, the larger estimate of internal noise in child listeners predicts a shallower psychometric function for intensity discrimination. Work currently underway will address the degree to which internal noise in child listeners, as estimated here, is consistent with the principals of signal detection theory.

Whereas it is not uncommon to consider internal noise as a qualitative factor in children's psychophysical data, it is not commonly quantified, as it was for these data. One exception is a study by Allen and Nelles (1996). That study estimated internal noise in adults and children for a frequency discrimination task and reported that internal noise was elevated for young children and reached levels comparable to that observed in adults by age 7. Because internal noise for the results of Experiment 2 was estimated based on ΔL in the *tone-steady* condition (that is, $\Delta L/1.61$), the effects of age on estimates of internal noise can be assessed directly based on those data. Figure 4 shows ΔL for individual child listeners in the *tone-steady* condition plotted as a function of age, with ±2 standard deviations around the mean adult threshold indicated in the shaded region. Here 10 out of the 15 child listeners fall above the 95% confidence interval for the adult performance. Those who fell within the confidence interval were, on average, older than the mean of the child group (8.8 yr as compared to 7.9 yr, respectively), consistent with the hypothesis that performance improves over this age range. A regression analysis failed to identify a significant age effect, however ($F_{1,13}$=1.79, p =0.20). A post-hoc power analysis indicates that if these data are representative of the population, it would be necessary to run approximately 55 listeners to obtain a significant correlation using a one-tailed criterion of α = 0.05, with a power of 0.8 (Cohen, 1988). A line fit to the resulting data would be quite poor at describing the time course of development in detail, however, with many more listeners necessary to reliably estimate the age at which the average performance becomes adult-like. These observations are qualitatively consistent with the individual differences previously noted in intensity discrimination in children (e.g., Jensen and Neff, 1993). It is difficult to assess whether the *tone-steady* thresholds reported here are consistent with the literature on intensity discrimination in school aged children given the variability both across studies and within the current dataset, but the present results are more consistent with the suggestion that development extends out to 10 yr of age (e.g., Fior and Bolzonello, 1987) than the suggestion that intensity discrimination may be adult-like in most children by age 5 yr (e.g., Jensen and Neff, 1993).

IV. SUMMARY AND CONCLUSIONS

In Experiment 1 thresholds for a tone-in-noise detection task were different for children and adults. Not only were thresholds elevated for children, but adults benefited more from stimulus features of low-fluctuation noise than children. Results of reduced-cue conditions revealed that both children and adults performed similarly with just level cues and with tone-in-noise conditions, which also provided level-invariant cues. Most adults could make use of level-invariant cues, but most of the children were at a ceiling on these tasks. While this result leaves open the possibility that some adults could have made use of multiple cues in a simple tone in noise task, performance with just the level cue was not significantly different from the case where all cues were present, suggesting that level-invariant cues likely contributed little to performance. There was an interaction between the stimulus type and the listener group for both conditions, where the level served as a cue to the presence of a signal; that is, adults performed better in the low-fluctuation than the Gaussian noise, while children showed no effect of stimulus type. This result led to the somewhat counterintuitive hypothesis tested in Experiment 2 that children are less susceptible to the effects of external stimulus variability than are adults.

Experiment 2 estimated intensity discrimination for a tonal standard and a Gaussian noise standard, with and without an interval-by-interval level rove applied to that standard. As predicted, data from child listeners showed less evidence of threshold elevation in response to stimulus variability. The general form of the data was fitted with a simple model of performance as a function of internal and external noise. The estimate of internal noise for children was a factor of 2.5 times greater than that estimated for adults, and the effect of this greater internal noise was to temper the effects of external noise on the performance of child listeners.

While the definition of internal noise has traditionally been quite broad, encompassing variability due to transduction noise, memory, criteria, and attention—in short, any variability not accounted for by external variability—the proposal tested here is more specific, namely that the neural representation of intensity is more variable in children than adults. The conclusion that poorer performance and greater internal noise, either described qualitatively (as in Exp 1) or modeled quantitatively (as in Exp 2), can account for an age effect is important to the interpretation of the result because it does not require that we think of development in terms of the maturation of multiple specialized processing abilities. Rather, a refinement in the auditory ability may appear to emerge at different ages simply by virtue of their sensitivity to one or a small set of variables underlying internal noise. More work is needed to assess the extent to which child listeners adhere to the assumptions underlying the simple signal detection model fitted here.

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APPENDIX A: ESTIMATING THRESHOLD BASED ON INTERNAL AND EXTERNAL NOISE

Thresholds in the conditions other than the *tone-steady* condition are substantially affected by stimulus variability, quantified as σ_e in Eq. (1). Implicit in this equation is the assumption that the noise is normally distributed around the mean, such that σ_e represents the standard deviation of a Gaussian distribution. The noise associated with stimulus fluctuation in the Gaussian noise stimuli was approximately normally distributed, with a slight skew (third moment) of −0.68, when represented in dB. The noise introduced by the rove, however, was clearly not normal, being based on a uniform distribution applied to the standard.

Rather than approximating external noise as normally distributed and predicting thresholds with Eq. (1), a MATLAB routine was written to generate cue distributions associated with the stimuli used here. At each of a range of signal levels, 5000 samples of signal present and 5000 samples of no-signal stimuli were generated using the same procedures as employed in

Experiment 2. Independent samples of Gaussian-distributed internal noise were then added to each estimate of signal level in each array, based on estimates of σ_i computed above. Pairs of signal-present and no-signal samples were subtracted, for a total of 5000 values of cue difference. The distribution of these differences was then used to estimate *d*', according to the formula

$$d' = \sqrt{2}\Delta / \sigma_{\mathrm{diff}}, \quad (A1)$$

where Δ is the signal level associated with the signal-present array and σ_{diff} is the standard deviation of the cue difference array. The scalar ($\sqrt{2}$) is introduced because the standard deviation of the difference between two distributions is $\sqrt{2}$ times the standard deviation of each contributing distribution, assuming they are of equal variance. In this way the *d*' associated with each signal level was computed. A total of 5 signal levels were used, spaced at 0.5 dB intervals and chosen adaptively to bracket the final estimate. The relationship between *d*' and signal level was well characterized in terms of a least-squares line fit, and this fitted line was used to estimate the signal level associated with d'' =1.61.

This process was repeated 8 times: 4 levels of external variability (*tone-steady*, *tone-roved*, *Gnoise-steady, and Gnoise-roved*) × two groups (child and adult, with σ_i =2.45 and σ_i =0.99, respectively). To give an indication of the reliability of these procedures, threshold estimates in the *tone-steady* condition computed using this procedure were within 0.1 dB of those computed analytically. Threshold predictions are indicated with dark lines in Fig. 3.

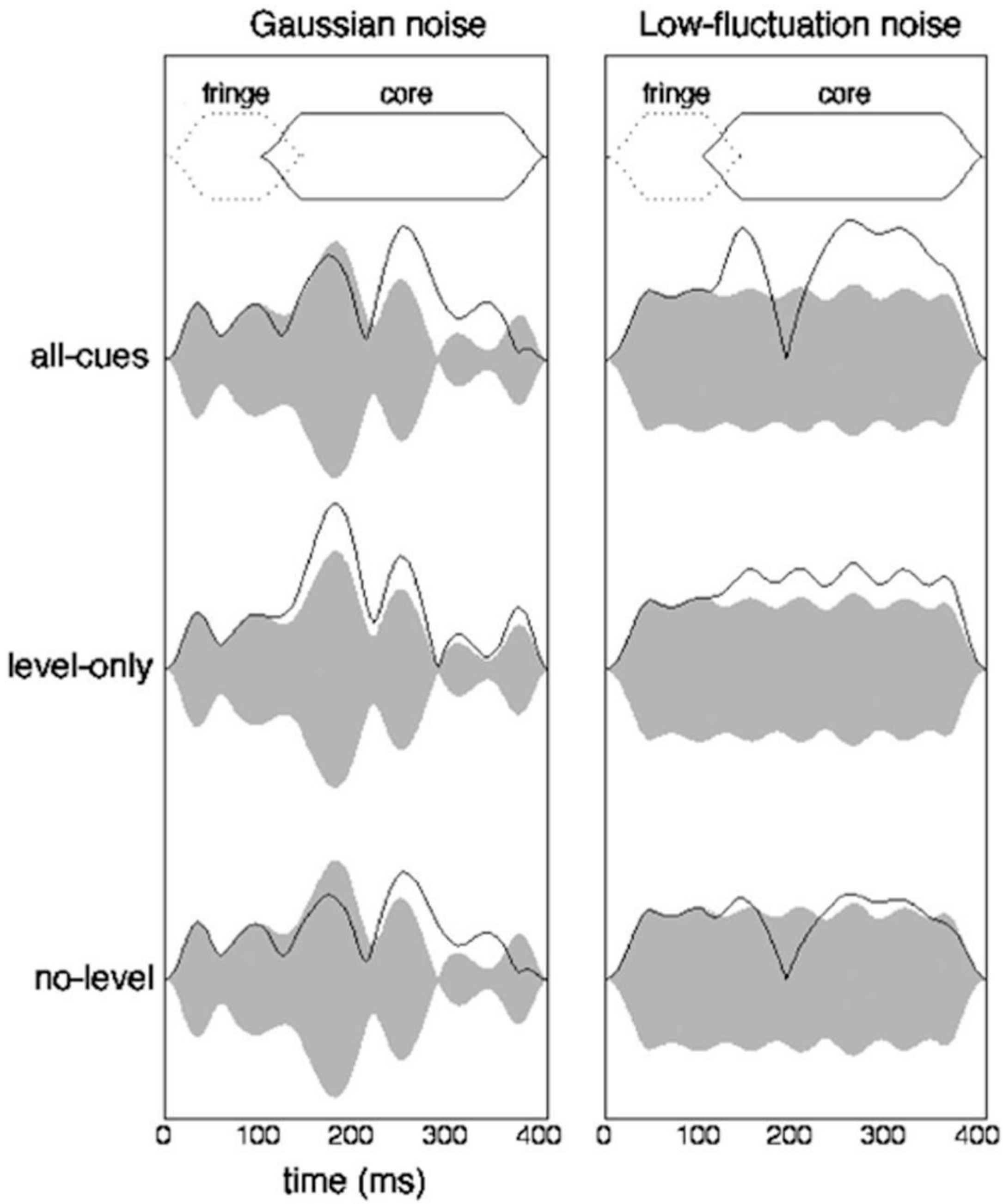

FIG. 1.
Example stimuli from Experiment 1 are shown, with Gaussian noise (left panel) and low-fluctuation noise (right panel), and signal conditions indicated in the left margin. The top row in each panel shows the segments of the stimulus identified as the *fringe* and core portions. The next row, labeled *all cues*, shows a standard stimulus (in gray) and the envelope of that standard summed with a 65-dB SPL pure tone signal (black line). The final two rows show standard and signal-plus-standard for the comparable *level-only* and *no-level* conditions. For illustrative purposes a single random sample was selected for all three signal conditions within each panel; in the experiment a new random sample was generated prior to each presentation.

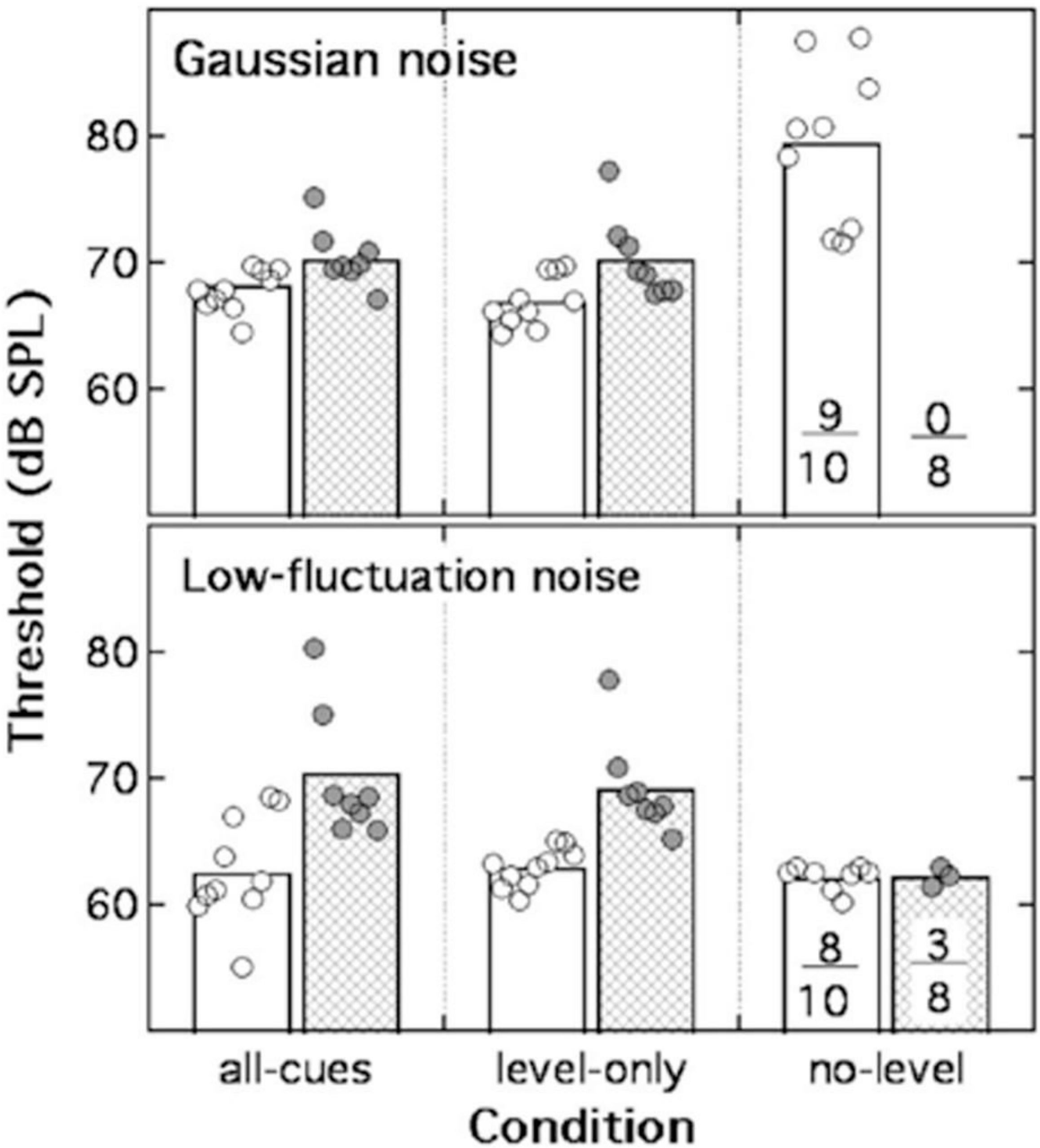

FIG. 2.
The mean thresholds from Experiment 1 are plotted for Gaussian noise (top panel) and low-fluctuation noise (bottom panel). Bar markings indicate mean data from adults (□) and children (⊠), and the circles associated with each bar show individual data. Stimulus conditions are indicated along the abscissa. The ratios at the right of each panel indicate the proportion of listeners contributing to each mean in the *no-level* conditions: individuals' data were omitted from the average if they were deemed to be indistinguishable from ceiling performance.

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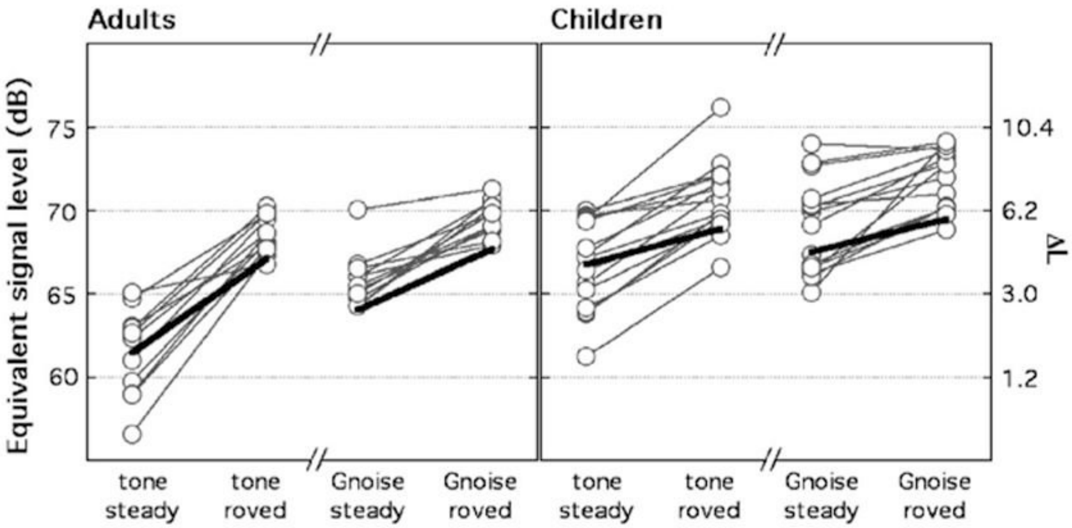

FIG. 3.

Individual data from Experiment 2 are shown in units of dB *as if* the signal had been added in random phase. The ordinate labels at the right show associated units of ΔL. Panels show results for adults (left panel) and children (right panel), with stimulus conditions indicated along the abscissa. Dark lines indicate fits to the data.

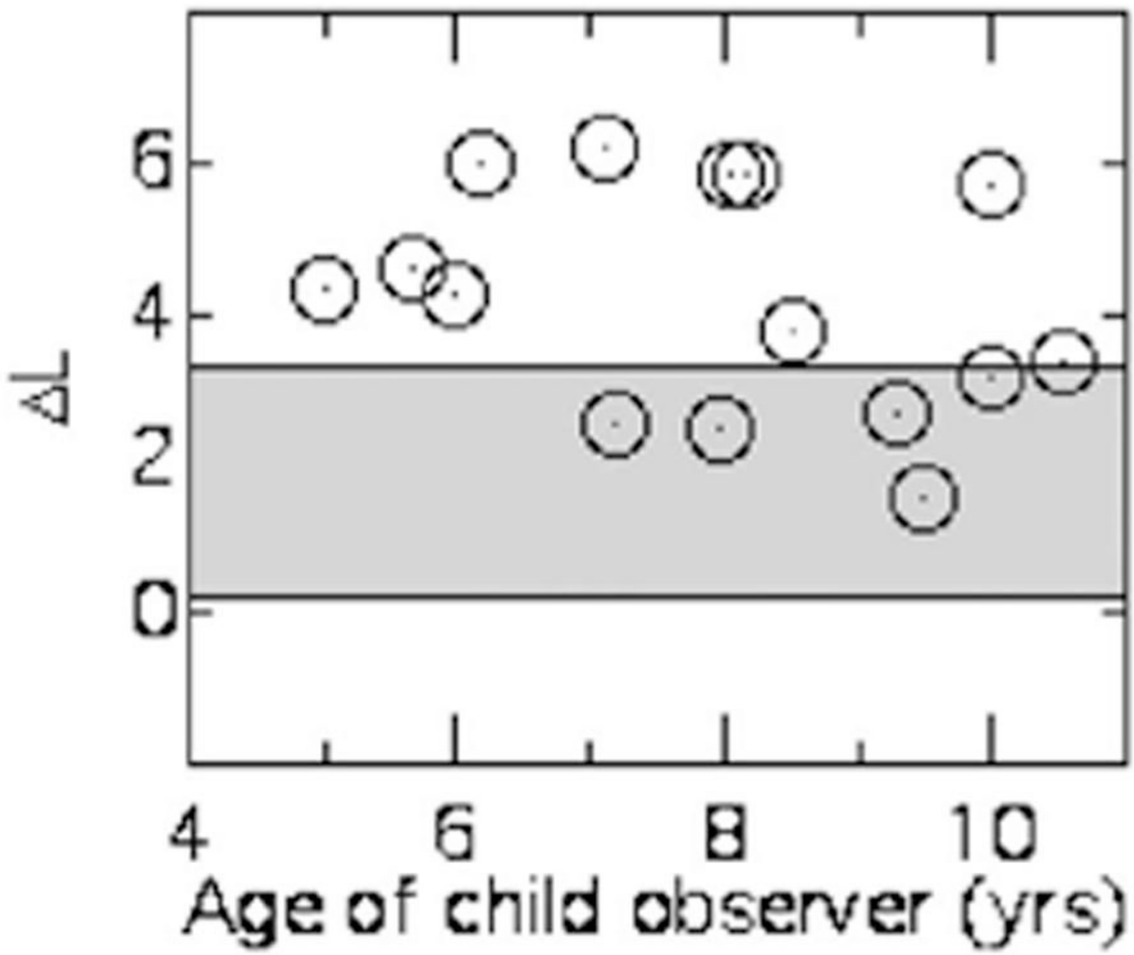

FIG. 4.
Individual data of child listeners in the *tone-steady* condition are plotted as a function of age. Consistent with units used to compute internal noise, data are plotted in units of ΔL, with ±2 std around the mean adult threshold indicated as the shaded region.