Effect of masker-frequency variability on the detection performance of infants and adults[a)]

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The effect of masker-frequency variability on the detection performance of 7–9 month-old infants and adults was examined. Listeners detected a 300-ms 1000-Hz pure tone masked by: (1) A random-frequency two-tone complex; (2) a fixed-frequency two-tone complex; or (3) a broadband noise. Maskers repeated at 300-ms intervals throughout testing at 60 dB SPL. The signal was presented simultaneously with one presentation of the masker. Thresholds were determined adaptively using an observer-based method. Infants' thresholds were higher than adults' in all conditions, but infants' and adults' thresholds changed with masker condition in qualitatively similar ways. The fixed two-tone complex produced masking for both age groups, but more masking for infants than for adults. For infants and adults, the random two-tone complex produced more masking than broadband noise, but the difference was greater for infants than for adults. For infants and adults, the random two-tone complex produced more masking than the fixed two-tone complex, and the difference between these conditions was similar for both age groups. These results suggest that infants are more susceptible to informational masking than adults in the absence of spectral variability. Whether infants are more susceptible to the effects of masker-frequency variability than adults remains to be clarified. [DOI: 10.1121/1.2200150]

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I. INTRODUCTION

Acoustic variability is inherent in the natural environment of a developing infant. Relevant signals can occur at unpredictable times, particularly when the listener has limited experience with sounds. Moreover, the spectral, amplitude, and temporal characteristics of these signals are dynamic and variable. Understanding how infants learn to identify and distinguish important acoustic signals from a variable background is critical if we hope to understand how hearing develops.

Many investigators have examined the effects of stimulus variability on the detection and discrimination performance of trained adults (e.g., Watson *et al.*, 1975; Neff and Green, 1987; Neff and Callaghan, 1988; Neff and Dethlefs, 1995; Kidd *et al.*, 1994; Kidd *et al.*, 2003; Oh and Lutfi, 1998; Richards and Neff, 2004; Alexander and Lutfi, 2004). In this context, stimulus variability is created by randomly changing the acoustic properties of either the relevant target (the signal) or the irrelevant background (the masker). Considerable masking can be produced by varying the frequency content of the masker with each presentation; threshold elevations as high as 50 dB have been observed for fixed-frequency signals in the presence of random-frequency multitone maskers (e.g., Neff and Green, 1987). Unlike peripheral or "energetic" masking, this masking can be observed when the frequency components that comprise the masker are located well outside the auditory filter centered on the signal. That is, masking is observed even though the peripheral auditory system provides sufficient resolution to prevent the masker from affecting the audibility of the signal. In the literature, masking produced in excess of energetic masking (Fletcher, 1940) has been referred to as "informational" masking (reviewed by Durlach *et al.*, 2003b).

Informational masking is widely believed to involve central auditory processes and may reflect difficulties in such complex auditory skills as sound source segregation (e.g., Kidd *et al.*, 1994; Neff, 1995)—the process by which acoustic components are identified as coming from one or more sound sources—and analytic listening strategy (e.g., Lutfi *et al.*, 2003b)—the extent to which a listener attends to the relevant signal of a complex sound and ignores irrelevant maskers. However, the mechanisms responsible for informational masking are not fully understood. In part, this lack of understanding reflects the difficulty involved in accounting for the large differences in performance observed across individuals.

Recently, investigators have had considerable success accounting for these large individual differences using Lutfi's component-relative-entropy (CoRE) model (Lutfi, 1993). The CoRE model is similar to models of energy detection in that it assumes detection is based on the energy output of the auditory filter centered on the signal frequency. However, the CoRE model differs from traditional energy-detector models by considering potential contributions from auditory filters not centered on the signal frequency. Investigations by Lutfi

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and his colleagues have demonstrated that individual differences in informational masking are largely related to differences in the number and the frequency range of monitored auditory filters. For example, Alexander and Lutfi (2004) have shown that weighting efficiency, the extent to which a listener exclusively monitors the auditory filter centered on the signal frequency, successfully predicted the amount of informational masking. Listeners with high weighting efficiencies were resistant to informational masking whereas listeners with low weighting efficiencies were susceptible to informational masking. Presumably, adult listeners generally have high weighting efficiencies when masker variability is reduced.

Although decision weights have not been obtained from infants under similar conditions, perceptual development might be expected to influence performance in the presence of masker-frequency variability. It is interesting to note similarities between adults' performance in informational masking tasks and infants' performance in conventional psychoacoustic tasks, including elevated detection thresholds and large individual differences. Several findings suggest that infants' weighting efficiency under conditions of low stimulus variability is similar to that of adults under conditions of high stimulus variability. For example, Bargones and Werner (1994) measured "listening bands" for 7- to 9-month-old infants and for adults using the probe-signal paradigm (Greenberg and Larkin, 1968). During a typical probe-signal task in the frequency domain, listeners detect tones in noise, and a single "expected" frequency target signal is presented on the majority of trials. Probes at other "unexpected" frequencies are presented on a minority of trials. In the Bargones and Werner study, adults detected the expected signal at a higher rate than the unexpected probes. This result is consistent with previous results from other laboratories and indicates that adults listen selectively for an expected frequency in a detection task, effectively enhancing detection of the expected frequency at the expense of unexpected frequencies (e.g., Dai *et al.*, 1991). In terms of the CoRE model, adults do not detect unexpected frequencies because they give little weight to the output of filters centered on the unexpected frequencies. In sharp contrast, infants did not appear to listen selectively in the frequency domain. Infants detected expected and unexpected frequencies equally well, suggesting that they give weight to auditory filters centered at unexpected frequencies.

A consequence of infants' inefficient weighting strategy is that they exhibit masking in conditions where neither energetic nor informational masking has been observed in adults. For example, Werner and Bargones (1991) have described "distraction effects" in 6-month-old infants. Thresholds for a 1000-Hz pure tone were measured in quiet and in the presence of a bandpass noise. The noise (4000–10,000 Hz) was higher in frequency than the 1000-Hz tone and was presented at an overall level of 40 dB SPL. Adult thresholds were similar in noise and in quiet. In contrast, infant thresholds were elevated by approximately 10 dB in the presence of the noise relative to thresholds obtained in quiet. Furthermore, infant thresholds did not change when the level of the noise was changed from 40 to 50 dB SPL. Given that the frequency of the noise band was remote from the auditory filter of the 1000-Hz signal and that increasing the level of the noise did not further increase infants' thresholds, it is difficult to attribute the threshold elevations to energetic masking. Investigations of infants' psychometric function for detection also support the idea that infants use an inefficient weighting strategy (Bargones *et al.*, 1995; Werner and Boike, 2001). However, note that infants apparently have a low weighting efficiency for pure-tone detection when the masker frequency is fixed. Put another way, infants act like uncertain adults even when the stimuli are not variable. We use the term "variability" to refer to the characteristics of the sound, and the term "uncertainty" to refer to the presumed variability in the sensory effects of sound, because effects of internal and external variability might vary with development.

Although informational masking has not been systematically examined during infancy, it has been examined during the preschool period (e.g., Allen and Wightman, 1995; Hall *et al.*, 2005; Oh *et al.*, 2001; Wightman *et al.*, 2003; Wightman and Kistler, 2005). Studies have consistently reported that young children are more susceptible to the effects of masker-frequency variability than adults. For example, Allen and Wightman (1995) obtained detection thresholds for a 1000-Hz pure tone in the presence of broadband noise alone and in the presence of a broadband noise plus a one-component random-frequency tonal masker in a group of adults and a group of 3–5-year-old children. The average adult threshold obtained in the combined noise and random tone condition was 66.2 dB SPL compared with an average child threshold of 81 dB SPL. Note that the data of only 7 of 17 preschoolers tested were used to calculate this average threshold. The remaining children had detection thresholds above 90 dB SPL. Thus, children generally performed much worse than adults. However, large individual differences in performance were evident for both age groups. Among the seven children who provided measurable thresholds, the difference in threshold between the noise-plus distracter and the noise-alone conditions was often similar to that observed for many of the adults. In another study, Oh *et al.*, 2001 obtained thresholds from preschoolers and adults for a 1000-Hz pure tone presented simultaneously with either a broadband or a multitone masker comprised of 2 to 906 components. The amplitude and frequency of each component of the multitone masker varied randomly on each presentation. Both groups demonstrated large individual differences in threshold in the presence of the multitone masker. However, the average child's threshold was worse than the average adult's threshold. For some children, as much as 83 dB of masking was observed. In contrast, only small age differences in masking were observed for the broadband noise masker. Recently, Lutfi *et al.* (2003b) have asked whether individual differences in informational masking, including differences between children and adults, reflected fundamental differences in detection strategy rather than age differences in weighting efficiency. Principal component (PC) analysis was used to determine the number of PCs that were required to account for the variance in individual informational masking. The hypothesis was that if children and adults used qualitatively different detection strategies, at least two PCs would be required. The results indicated that a single PC accounted for 83% of the variance within and across age groups, and that PC was highly correlated with the number of auditory filters the listener monitored in detection. Preschoolers generally monitored a greater number of filters than did adults, suggesting that the apparent increase in susceptibility to informational masking observed during the preschool period occurs because children listen less selectively and monitor more filters than adults do during these tasks. This finding is consistent with those of Werner and Bargones (1991) and Bargones and Werner (1994), except that preschoolers appear to monitor a larger number of filters under conditions of masker-frequency variability while infants appear to do so even when masker frequency is fixed. To our knowledge, no published studies have examined preschoolers' listening strategies for the detection of a fixed-frequency pure tone signal in the presence of fixed-frequency remote maskers.

The purpose of the current investigation was to examine the detection performance of infants under conditions of masker-frequency variability. It was difficult to predict how infants would perform under such conditions. Given the apparent susceptibility to informational masking observed during the preschool period, informational masking effects might be very large during infancy, with large differences in performance across infant subjects. Alternatively, variability is often high during times of rapid maturation. Perhaps listening abilities develop more slowly during infancy than during the preschool period. As a result, infants' performance might be consistently poor. Finally, infants appear to use an inefficient weighting strategy in the absence of masker-frequency variability, monitoring irrelevant auditory filters. One explanation for this phenomenon could be that infants' internal representation of the stimulus varies, even when the stimulus does not. The introduction of physical stimulus variability might have little additional effect on infants' performance.

II. METHOD

A. Listeners

The listeners were 33 7–9-month-old infants and 31 18–30-year-old adults. The average age at the initial testing session was 32.9 wk [standard deviation (SD)=4.1 wk] for infants and 21.4 yr (SD=1.7 yr) for adults. Listener selection criteria included: (1) No risk factors for hearing loss as assessed by parent or self-report, (2) no more than two episodes of otitis media, (3) not under treatment for otitis media within the prior week, and (4) healthy on the test date. In addition, screening tympanometry was performed on every subject at each session. Peak admittance of at least 0.2 mmhos at a pressure between −200 and 50 daPa was required to pass the screening. No adult listener had more than two years of musical training nor had any listener participated in previous psychoacoustic studies. An additional seven infants and one adult were tested but were excluded from data analysis, because they did not meet the training or testing criteria.

B. Stimuli and equipment

For all conditions, the signal was a 1000-Hz pure tone. The duration of the signal was 300-ms, including a 10-ms rise/fall time. There were three types of maskers: Random-frequency two-tone, fixed-frequency two-tone, and broadband noise (300–3000 Hz). Both the random and fixed two-tone maskers consisted of two simultaneous components. The rationale for using a two-component masker is that this condition tends to produce lower thresholds relative to 10- and 20-component maskers, but the largest range in performance across listeners (e.g., Neff and Dethlefs, 1995). Thus, maturational effects might well be expected. In addition, any masking produced by two remote-frequency masker components is unlikely to be energy-based. For the random two-tone masker, one component was drawn at random from a rectangular distribution with a range of 300–920 Hz. The second component was drawn at random from a rectangular distribution with a range of 1080–3000 Hz. The "protected region" of 920 to 1080 Hz around the signal frequency was designed to reduce the possible contribution of peripheral (energy-based) masking within a presumed auditory filter centered at the signal. For the fixed two-tone masker, the two components were 581-Hz and 2920-Hz pure tones.[1] The general properties (e.g., two flanking tones, stimulus level) of the fixed-frequency masker were designed to match those of the random-frequency masker, but the frequency content of the masker remained unchanged throughout testing. The rationale for including a fixed two-tone masker condition is that it provides a comparison condition of minimal acoustic variability. In contrast to the minimal-variability broadband noise condition, the fixed two-tone condition is expected to produce little or no energy-based masking. Maskers were repeated at 300-ms intervals throughout the entire testing session. The signal, when present, was gated synchronously with one presentation of the masker. All maskers were presented at a total power of 60 dB SPL. A schematic representation of the stimuli is presented in Fig. 1.

Stimuli were generated digitally and then low-pass filtered at 4000 Hz using Tucker-Davis Technologies (TDT) system III programmable hardware (RP2). The signal and masker were attenuated separately using two programmable attenuators (TDT PA5), mixed, and fed to a headphone buffer (TDT HB7). The experiment was controlled by a computer using custom software. Testing was conducted in a double-walled sound-attenuating room (IAC). All stimuli were presented to the listener's right ear through an ER1 insert earphone. When necessary, the foam tip of the insert earphone was trimmed to fit the ear canal.

C. Procedure

Listeners were randomly assigned to one of the three masker conditions. Adults were tested in a single visit to the laboratory. Infants were tested in three separate visits occurring within a 2-wk period. Visits for both age groups were approximately 45 min in length. For listeners who completed testing quickly enough, data were collected in a second masker condition. The assignment of the second masker condition was also random.

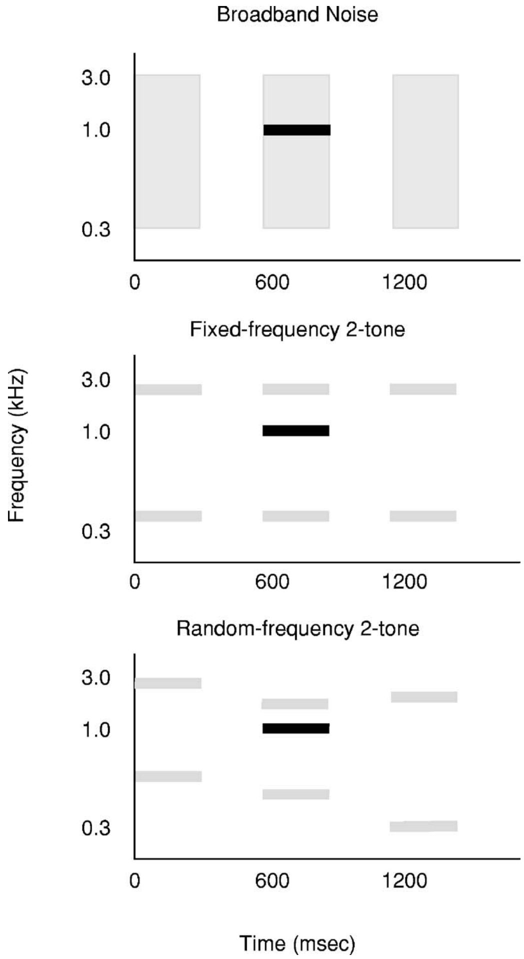

FIG. 1. Schematic illustrations of stimuli in the form of a spectrogram. Three repetitions of the continuously repeating masker (light shading) are illustrated, with the signal (bold) added to the second masker repetition. The signal, when present, was played synchronously with one repeat of the masker.

An observer-based procedure was used to assess infants' performance (Werner, 1995), and the test procedure for adults was kept as similar to that for infants as possible. Infants were tested sitting on their parent's lap. An assistant sat to the left of the parent and infant and manipulated quiet toys in order to keep the infant facing toward the midline. To prevent the assistant and the parent from hearing the tones and influencing the infant's response, both wore circumaural headphones that delivered masking sounds. Adult listeners were tested alone in the booth. To the listener's right were two mechanical toys with lights in a dark Plexiglas box. An observer sat outside of the booth and initiated trials when the listener was quiet and facing midline.

Trials were either "signals" in which the 1000-Hz tone was presented simultaneously with one burst of the repeating masker, or "no signals" in which only the masker was presented. The observer did not know which type of trial occurred and was required to decide on the trial type based on the listener's behavior within 4 s of trial onset. The listener was provided with reinforcement if the observer correctly identified a signal trial. Reinforcement was the activation and illumination of a mechanical toy. For infant listeners, any response that reliably distinguished between signals and no-signals could be used by the observer; these typically included head turns or eye movements toward the reinforcer or changes in activity. Adult listeners were instructed to raise a hand when they heard "the sound that makes the toy come on", and the observer recorded those responses that occurred during trials. Feedback was provided to the observer after every trial.

Sessions consisted of two training phases and one testing phase. In both training phases, the signal was presented at a level that was expected to be clearly audible, depending on the masker condition and based on previous studies and pilot work. The purpose of the first training phase was to demonstrate the relation between the signal and the mechanical reinforcer. Thus, the probability of a signal was 0.80 and the listener was reinforced after each signal trial, regardless of the observer's response. The first training phase ended when the observer correctly responded to four of five consecutive trials, including at least one no-signal trial. The purpose of the second training phase was to demonstrate to the listener that he needed to respond to signal trials in order to activate the mechanical toy. The probability of a signal was 0.50, and reinforcement was only provided if the observer correctly identified a signal trial. The second training phase ended when the observer achieved a hit rate of 0.80 and a false alarm rate of no greater than 0.20. Infants required an average of 38.2 (SD=13.5) trials to complete both training phases. In comparison, adults required an average of 17.8 (SD=7.3) trials to complete both training phases. There were no significant differences in the number of trials required to complete training across condition in either age group.

During testing, the probability of a signal trial was 0.75 and the probability of a no-signal trial was 0.125. Probe trials, on which the level of the target tone was the training level, were presented with a probability of 0.125. Detection thresholds were estimated adaptively using a one-up two-down algorithm (Levitt, 1971). Only signal trials affected the direction of the adaptive track and step size varied during a run following PEST rules (Taylor and Creelman, 1967). Based on pilot data, the starting level for the signal was approximately 10 dB above the expected threshold value. The initial step size was 6 dB. Testing continued until eight reversals were obtained and threshold was calculated as the average of the last six reversals. Thresholds were only accepted if the probe response rate was greater than 0.60 and the false alarm response rate was lower than 0.40. Ideally, a bias-free measure should be used to estimate sensitivity. However, informational masking data have not been collected previously in infants, and it is difficult and time consuming to obtain a psychometric function from an infant. Thus, we chose to estimate infants' sensitivity using an adaptive procedure in order to characterize the general effects of masker-frequency variability during infancy in this initial study. Limiting the acceptable false alarm rate was expected to provide some control of response bias. Additional analyses addressing this issue are described in the results.

The same experimental phases and psychophysical procedures were used to test infants and adults. Thus, from the listener's perspective, the testing conditions were the same for infants and adults: Trials were not defined and occurred

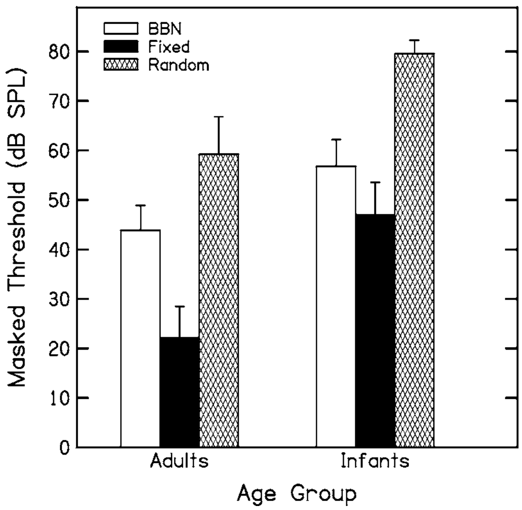

FIG. 2. Mean thresholds (±1 SD) are shown as a function of masker condition for adults and infants. The open, filled, and shaded bars represent the broadband noise, fixed two-tone, and random two-tone conditions, respectively.

at irregular intervals, and responses to signals produced activation of the mechanical toy, while responses at other times did not. It is important to note that the timing of signal presentations is variable in this procedure for all conditions. Although the introduction of temporal variability is appealing in the sense that it is probably closer to real world conditions, the effects of temporal and frequency variability might interact in such a way that the effects of frequency variability observed may not be generalizable to conditions of low temporal variability, and thus may limit the comparability of the results to those of previous studies.

Listeners were initially assigned to one masker condition. Thresholds were obtained from 13 infants in the broadband noise masker condition, 9 infants in the fixed two-tone masker condition, and 11 infants in the random two-tone masker condition. Thresholds were obtained from 11 adults in the broadband noise masker condition, 10 adults in the fixed two-tone masker condition, and 10 adults in the random 2-tone masker condition. Given the potential for large individual differences in performance, we tested listeners in two masker conditions whenever possible. A total of 17 infants and 24 adults were tested in two masker conditions. Six infants and seven adults were tested in both the broadband noise and fixed two-tone masker conditions. Four infants and seven adults were tested in both the broadband noise and random two-tone masker conditions. Seven infants and ten adults were tested in both the fixed two-tone and random two-tone masker conditions.

III. RESULTS

Two sets of analyses were undertaken, a between-subjects analysis based on the data of 64 listeners and a within-subjects analysis based on the data of 41 listeners.

A. Between-subjects analysis

Figure 2 shows the average threshold estimates in dB SPL for each age and masker condition. For listeners providing data points in two conditions, only the initial threshold was included in these averages. As expected, the average infant threshold was higher than the average adult threshold in all conditions. However, the threshold changed with condition in a similar way for the two age groups. The average threshold within each age group was lowest in the fixed two-tone condition, intermediate in the broadband noise condition, and highest in the random two-tone condition. One apparent difference between the age groups is that while the adults' threshold in the fixed two-tone condition is considerably lower than their threshold in both of the other conditions, infants' threshold in the fixed two-tone condition is not much lower than their threshold in the broadband noise condition. The average adult threshold in the fixed two-tone condition is roughly 22 dB lower than the average adult threshold in the broadband noise condition and 37 dB lower than in the random two-tone condition. The average infant threshold in the fixed two-tone condition is only 10 dB lower than the average infant threshold in the broadband noise condition and 33 dB lower than in the random two-tone condition. It should be noted that the adults' threshold in the fixed-frequency two-tone condition, about 22 dB SPL, is higher than the expected threshold for a 1000-Hz tone in quiet.

An analysis of variance (*ANOVA*) confirmed the trends observed in Fig. 2. All of the effects in the Condition X Age analysis were significant: Condition $[F(2,58)=185.98, p<0.001]$, Age $[F(1,58)=180.48, p<0.001]$, and Condition X Age $[F(2,58)=5.962, p=0.004]$. The significant Condition X Age interaction suggests that the differences between conditions are not the same in the two age groups. To explore the nature of the interaction, a one-way ANOVA was performed within each age group. This analysis revealed a significant main effect of condition for adults $[F(2,28)=86.02; p<0.001]$ and for infants $[F(2,30)=112.96; p<0.001]$. *Post hoc* testing (Scheffe, using a criterion of $p<0.05$) indicated thresholds were lower in the fixed two-tone than in the noise condition, thresholds were lower in the noise condition than in the random two-tone condition, and thresholds were lower in the fixed two-tone than in the random two-tone condition, for both infants and adults. A two-way ANOVA (Condition X Age) was then performed on each pair of conditions to identify the source of the Condition X Age interaction in the omnibus analysis. A significant Condition X Age interaction was observed for the broadband noise and random two-tone conditions $[F(1,41)=5.29, p=0.027]$, indicating a larger difference between conditions for infants than for adults. The comparison between broadband and random-frequency masking is the one made in previous studies of children, and the relatively larger increase in average threshold in the random-frequency condition among infants is consistent with the results of those studies. In contrast, there was no Condition X Age interaction for the fixed- and random-frequency two-tone conditions $[F(1,36)=1.39, p=0.25]$, providing no evidence that adding masker-frequency variability to a two-tone masker affected infants' performance any more than it affected adults'. A significant Condition X Age interaction was found for the broadband noise and fixed two-tone conditions $[F(1,39)=11.15, p=0.002]$, indicating that the difference between the fixed two-tone and the broadband noise

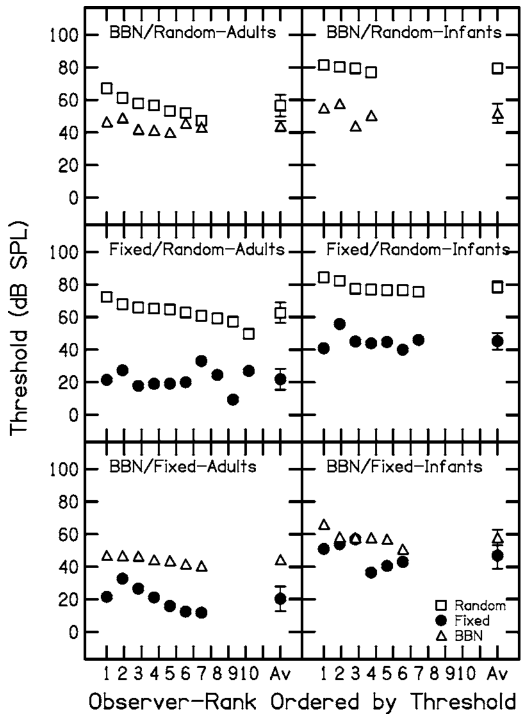

FIG. 3. Thresholds are plotted for individual adults and infants and for the average across listeners (Av). The error bars indicate ±1 SD. Panels are for listeners tested in the broadband noise and random two-tone conditions (top row), the fixed two-tone and random two-tone conditions (middle row), and the broadband noise and fixed two-tone conditions (bottom row). Adult thresholds are shown in the left panel and infant thresholds are shown in the right panel. The random two-tone, fixed two-tone, and broadband noise conditions are indicated using squares, filled circles, and triangles, respectively.

conditions was smaller for infants than for adults. This result suggests that infants are more susceptible to masking in the fixed two-tone condition than adults.

B. Within-subjects analysis

Because of large individual differences in informational masking (and among infants in all kinds of masking), it is important to determine whether the effects seen in the group comparisons are evident in the data of individual listeners. Figure 3 shows threshold estimates for individual listeners tested in two masker conditions, with adult data presented in the left panel and infant data presented in the right panel. The squares, filled circles, and triangles are for the random two-tone, fixed two-tone, and broadband noise masker conditions, respectively. The individual listeners are rank ordered from highest to lowest threshold in each panel. The average thresholds are plotted at the right of each panel. Note that the average thresholds plotted in Fig. 3 are quite similar to those of the larger groups (Fig. 2). Three-way repeated-measures *ANOVA* (Condition X Age X Order) of threshold for each condition pair showed that the same effects were significant as in the between-subjects comparison. The effect of Order was not significant in any of these analyses (all $p > 0.40$).

In most conditions, the effects observed in the individual data are similar to those in the group data. For the broadband-noise/random two-tone comparison, all four infants demonstrated larger differences in threshold than any of the adults. For the fixed two-tone/random two-tone comparison, the difference in threshold for the infants ranged from 26–44 dB compared with a range of 23–51 dB for the adults. For the broadband-noise/fixed two-tone comparison, several adults have broadband/fixed threshold differences as large as 30 dB, and no adults have threshold differences less than 15 dB. Interestingly, three of six infants look similar to adults in that their thresholds are 15–20 dB higher for the broadband-noise relative to the fixed two-tone condition. The remaining three infants show little or no difference in threshold between the broadband-noise and fixed two-tone conditions. Thus, some infants demonstrate considerable masking in the fixed two-tone condition, and some infants demonstrate about as much masking as many adults. These individual differences could not have been identified from the mean thresholds.

Note that considerable between-subjects variability was evident for both infants and adults. Infants and adults were about equally variable in the broadband noise and fixed two-tone conditions, and there was no apparent difference in variability between those two conditions. However, in the random two-tone masker condition, infants were less variable, while adults were more variable than infants and more variable than in the other masker conditions. The same trends are evident in the group data (Fig. 2).

C. Ceiling effects

The average infant threshold in the random two-tone condition was 79.6 dB SPL, with individual thresholds ranging from 75.5 to 84.4 dB SPL. Standard errors of 1.5, 2.2, and 0.8 dB were obtained for infants in the broadband noise, fixed two-tone, and random two-tone conditions, respectively. In contrast, standard errors of 1.5, 2.0, and 2.4 dB were obtained for adults in the broadband noise, fixed two-tone, and random two-tone conditions, respectively. Thus, the standard errors of infants and adults were comparable in all but the random two-tone condition. Because the range of thresholds obtained from infants was smaller than the range of thresholds obtained from adults in this condition, and because the maximum allowable level of the signal was 91 dB SPL, we examined the possibility that infant thresholds in the random two-tone condition were constrained by ceiling effects.

In fact, there were few indications in the data that many infants' thresholds in the random two-tone condition were much higher than those included in the analysis. Infants did not appear to have more difficulty completing training in the random two-tone condition relative to the other two conditions. The average number of trials required to complete training was 39, 33, and 43 for the broadband noise, fixed two-tone, and random two-tone conditions, respectively, and these were not significantly different. For infants assigned to the random two-tone masker condition, 13/15 successfully completed the two training phases and proceeded to testing. In comparison, 14/15 infants assigned to the broadband noise masker condition and 9/10 assigned to the fixed two-tone masker condition successfully completed the two training phases. The proportions of infants meeting training criteria

TABLE I. The average d's across listeners are compared for the between-subjects and within-subjects data. Standard deviations of the mean and range of d's are also shown for each set of data.

Between-subjects							
Infants				Adults			
Condition	d′	S.D.	Range	Condition	d′	S.D.	Range
BBN	0.92	0.39	0.39-1.61	BBN	1.74	0.36	0.81-2.18
Fixed	0.88	0.53	0.30-1.90	Fixed	1.91	0.15	1.68-2.14
Random	1.21	0.56	0.44-2.12	Random	1.81	0.36	1.22-2.46
Within-subjects							
BBN	1.06	0.54	0.40-1.82	BBN	1.75	0.22	1.52-2.09
Fixed	0.81	0.24	0.51-1.23	Fixed	1.82	0.24	1.39-2.06
BBN	1.20	0.90	0.56-1.61	BBN	1.79	0.39	0.92-2.14
Random	1.22	0.52	0.87-2.12	Random	1.94	0.29	1.64-2.46
Fixed	0.84	0.32	0.48-1.44	Fixed	1.87	0.18	1.65-2.14
Random	0.94	0.46	0.44-1.64	Random	1.68	0.31	1.22-2.15

who also completed testing were 11/13 for the random two-tone masker condition, 13/14 for the broadband noise masker condition, and 9/9 for the fixed two-tone masker condition. The average range of the reversals used to calculate infants' thresholds was similar in the three conditions: 4.6, 4.1, and 4.0 dB for the broadband noise, fixed two-tone, and random two-tone conditions, respectively. Only one infant's data were excluded from analysis because the next stimulus level called for by the adaptive algorithm exceeded 91 dB SPL. That infant was in the random two-tone condition, but if many infants' thresholds in the random two-tone condition actually were higher than 91 dB SPL, we would have expected more than one infant to be excluded for this reason. In summary, there is little evidence of a ceiling effect in the random two-tone masker condition for infants.

D. Response bias

In the current study, listeners were tested using a yes-no procedure in which only responses on signal trials affected the value of threshold. Thus, while the threshold should consistently indicate the stimulus level yielding a 71% hit rate, it may not indicate equivalent sensitivity if there were differences between ages or conditions in response bias. Furthermore, the average false alarm rate in the test phase of the procedure was 0.26 for infants, while it was 0.03 for adults.

To examine this issue, d' near threshold was calculated for each listener and experimental condition. Because threshold was estimated adaptively, the d' estimates were based only on trials after the adaptive track had stabilized (± 1 SD of the reversal points for each listener). Because the level is fairly constant for these trials, the expectation is that the listener's sensitivity and response bias are also fairly constant. A value of 0.5 was added to all cells in all conditions due to the high number of listeners having a false alarm rate of 0 (Snodgrass and Corwin, 1988).

Table I provides average estimates of d' for the group data and for listeners tested in two masker conditions. For all conditions, infants produce a d' of about 1, a value roughly

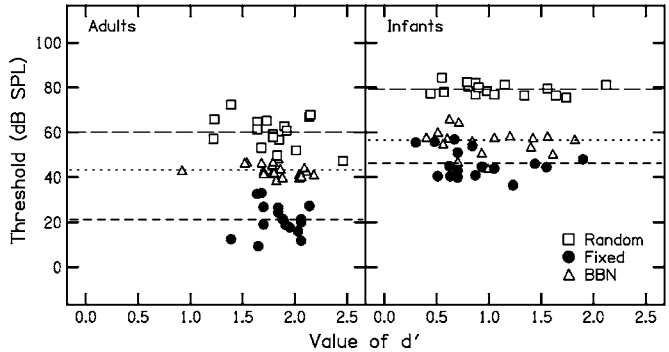

FIG. 4. d' values are plotted against threshold for individual listeners. Panels are for adults (left panel) and infants (right panel). Both the between-subjects and within-subjects data are included. The random two-tone, fixed two-tone, and broadband noise conditions are indicated using squares, filled circles, and triangles, respectively. The dashed horizontal lines indicate group mean thresholds for the random two-tone, broadband noise, and fixed two-tone conditions, from top to bottom in each panel.

consistent with 70% correct responses for an unbiased observer. In contrast, the average d' estimates for adults, 1.7–1.9, were consistently higher than those for infants, suggesting that at the estimated threshold adults are operating at the equivalent of 80% correct for an unbiased observer. Thus, it is likely that the overall difference between infants and adults in sensitivity is greater than the age difference in thresholds would suggest. There is no evidence, however, of systematic differences in d' across condition within either age group. This conclusion is supported by Fig. 4, where individual thresholds are plotted against d' by condition. While d' is variable, the range of d' estimates is similar across condition within each age group. In contrast, a clear relation between condition and threshold is evident for both the infant and adult data, and threshold differences are similar regardless of d'. Thus, the between-condition differences within age groups would not be greatly affected by differences in response bias. The trends in d' observed in Fig. 4 were confirmed in a Condition X Age ANOVA. The main effect of Age was significant $[F(2,58)=66.15, p<0.0001]$, indicating that d' estimates differed between infants and adults. Unlike the ANOVA performed on threshold, however, neither the main effect of Condition nor the Age X Condition interaction was significant (both $ps>0.4$).

IV. DISCUSSION

The major question addressed by this study was how masker-frequency variability affects infants' detection of a fixed-frequency pure tone. The results indicate that infants have higher masked thresholds than adults under conditions of masker-frequency variability. Further, the difference between infants' threshold in the presence of a broadband noise masker and their threshold in the presence of a random-frequency two-tone masker is greater than the difference seen in adults. These results were evident in between-group comparisons, as well as in the data for individual infants and adults tested in both conditions. This result matches one prediction offered in the introduction that informational masking effects might be very large during infancy, as they appear to be during the preschool period. However, the substantial between-subjects differences that characterize preschoolers' performance in the presence of masker-frequency variability were not evident in the infant data. Further, there was no overlap between the range of infants' thresholds and the range of adults' thresholds in the random two-tone condition.

In addition to the elevated masked thresholds observed under conditions of masker-frequency variability, both infants and adults demonstrated masking in the presence of a fixed-frequency two-tone masker. The amount of masking in this condition appeared, on average, higher for infants than adults. For some individual infants tested in both the fixed two-tone and broadband noise conditions, however, the amount of masking seen in the fixed two-tone condition, relative to the broadband noise condition, was within the range observed in adults.

Finally, thresholds in the random two-tone masker condition were higher than those in the fixed two-tone masker condition, for both infants and adults. The difference between these conditions should reflect the effect of masker-frequency variability in the presumed absence of energetic masking. Defining the effect in this way, there was no significant difference between infants and adults in the effect of masker-frequency variability. The random-fixed difference for all seven infants tested in both conditions fell well within the range of differences observed in adults. This result does not match well with any of our *a priori* predictions. The introduction of masker-frequency variability, in the presumed absence of energetic masking, was clearly detrimental to infants' performance, but there was no evidence that masker-frequency variability was more detrimental to infants' performance than to adults'.

A. Masking in conditions of minimal acoustic variability

Thresholds obtained here in the presence of intermittent broadband noise are comparable to infant and adult data reported in the literature for continuous broadband noise maskers using the same observer-based procedure (Bargones *et al.*, 1995). In addition, thresholds in noise for adults in the current study are similar to those expected for trained adults using more conventional two-interval forced-choice (2IFC) procedures with broadband noise maskers gated during observation intervals (e.g., Neff and Dethlefs, 1995).

The finding that infants had more difficulty than adults detecting a 1000-Hz tone in the presence of a broadband noise is consistent with previous investigations. Several observations suggest that the mechanisms responsible for infants' immature detection in noise are similar to the mechanisms responsible for informational masking in adults. There is evidence that infants monitor the output of many auditory filters during tone-in-noise detection tasks, whereas adults place little weight on filters remote in frequency from the tone (Werner and Boike, 2001; Bargones *et al.*, 1995; Bargones and Werner, 1994). As a result, thresholds are elevated because the signal-to-noise ratio is effectively decreased.

The infant-adult difference in threshold in broadband noise, however, is roughly 13 dB here, compared to a difference of 8 dB reported by Bargones *et al.* (1995). Because Bargones *et al.* estimated thresholds from a bias-free measure of sensitivity, and because adults were more conservative listeners than infants in the current study, we would expect that the infant-adult difference might be smaller in the current study, not larger. The basis for the discrepancy between studies is not clear, but the mode of masker presentation may have had a greater effect on infants' pure-tone detection than adults (Werner *et al.*, 2006). Bargones *et al.* used a continuous noise masker while we used a masker that was presented intermittently and that was gated on and off with the signal tone.

The fixed-frequency two-tone masking condition was included in the present experiment as a second comparison condition with minimal stimulus variability but with little or no possibility of energetic masking. We expected thresholds would be similar to those previously reported for a 1000-Hz signal in quiet, at least for the adults. This prediction was not met. The average adult threshold obtained in the fixed two-tone condition was 22.1 dB SPL (SD=6.4). In contrast, Werner *et al.* (2004) reported an average adult threshold of 10.6 dB SPL (SD=3.8) for a 1000-Hz pure tone in quiet using the same software, hardware, procedure, and transducer used here. Thus, the average adult threshold was approximately 11 dB higher in the fixed-frequency two-tone condition than the expected threshold in quiet. We did not, however, obtain thresholds in quiet in the current study. Because threshold in quiet can be variable across subjects, we tested an additional three adults in quiet as well as in the fixed-frequency two-tone masker condition. Condition order was randomized. Individual thresholds obtained for the three subjects in the fixed two-tone condition were 28.1, 19.3, and 14 dB SPL (mean=20.5 dB SPL). Thresholds in quiet for the same three subjects were 21.8, 1.6, and 11.4 dB SPL, respectively (mean=11.6 dB SPL). The average threshold obtained in the fixed-frequency two-tone condition for the three subjects was elevated by 10.4 dB relative to threshold in quiet. This estimate is similar to the 11 dB difference estimated from the group average adult data. Notice that the amount of masking in these three listeners ranged from less than 3 dB to nearly 18 dB, as is typical of informational masking. In a recent study, we confirmed that while many adult listeners demonstrate 3–5 dB of masking in the fixed-frequency two-tone masker condition, some exhibit 10–15 dB of masking (Werner and Leibold, 2005).

The group data suggest that both infants' and adults' detection was affected by the presence of a fixed-frequency two-tone masker remote from the signal frequency. However, the average infant's poor performance in this condition was striking. Average threshold was 22 dB higher in the broadband noise compared to the fixed two-tone condition for adults, but only 10 dB higher for infants. In addition, the average infant threshold measured in the presence of the fixed two-tone masker was elevated by approximately 18 dB relative to the average threshold in quiet estimated by Werner *et al.* (2004) with the same software, hardware, procedure, and transducer used here. This is similar to the observation of Werner and Bargones (1991) that infants' detection thresholds were elevated by about 10 dB when a remote-frequency band of noise was simultaneously presented with the signal. It would appear, however, that even more masking is observed when the remote-frequency masker is a tonal complex rather than noise.

For listeners tested in both the fixed two-tone and broadband noise masker conditions, the average effects are consistent with the effects observed in the group data. An examination of individual thresholds, however, revealed substantial variability in performance for infants tested in both conditions. Although one-half of the infants had higher thresholds in the broadband noise relative to the fixed two-tone conditions, thresholds for the remaining infants were similar in the fixed two-tone and broadband noise conditions. In contrast, all of the adult listeners tested in both the broadband noise and fixed two-tone conditions had lower thresholds in the fixed two-tone relative to the broadband noise condition. In other words, when energetic masking was reduced, all adults and some infants exhibited a "release" from masking, but some infants exhibited little or no improvement in threshold. Similarly, Werner and Bargones (1991) observed 0–30 dB of remote-frequency masking in infants, but only 0–7 dB in adults. The range of performance for infants in the fixed two-tone condition here is also similar to that reported in the literature for preschoolers under conditions of masker-frequency variability (e.g., Allen and Wightman, 1995; Oh *et al.*, 2001; Wightman *et al.*, 2003). Note, however, that the infants and adults whose fixed two-tone thresholds were 15–20 dB lower than their broadband noise thresholds were probably experiencing some masking in the fixed two-tone masker condition.

There is no apparent peripheral explanation for the masking observed in the presence of the fixed two-tone masker. Several other studies have also reported that thresholds for some adults in conditions with reduced masker-frequency variability (e.g., masker frequency fixed across intervals on each trial or across a block of trials) remain elevated above what would be predicted from energy-based detection (e.g., Alexander and Lutfi, 2004; Neff and Callaghan, 1988, Neff and Dethlefs, 1995; Richards and Neff, 2004). In the current study, the fixed-frequency masker consisted of pure tones at 581 and 2920 Hz, remote from the frequency region of the signal (Moore and Glasberg, 1996) and unlikely to produce substantial energetic masking. Further, at least two lines of evidence argue that the masking produced by the fixed frequency tonal masker should be considered informational masking. First, both the current and previous studies showed large individual differences in performance in fixed-frequency tonal masking conditions, as they do in random-frequency masker conditions. For example, Alexander and Lutfi (2004) reported thresholds ranging from 14.5 to 52.3 dB SPL in a group of normal-hearing adults asked to detect a 2000-Hz pure tone in the presence of a fixed-frequency ten-component masker used to estimate energetic masking (their $p=1.0$ condition). In contrast, listeners typically have similar and stable thresholds with broadband noise maskers. Second, Leibold *et al.* (2005) recently showed that temporal manipulations of the masker that reduced informational masking under conditions of masker-frequency variability also reduced adults' masking by fixed-remote-frequency maskers in a 2IFC task.

Thus, it appears that both infants and adults are susceptible to informational masking in the absence of masker-frequency variability. Although the mechanisms responsible for informational masking in this condition are unclear, Durlach *et al.* (2003a) have argued that stimulus uncertainty is not required to produce informational masking. Instead, it has been suggested that informational masking is largely determined by how much the signal and masker "sound alike" (Durlach *et al.*, 2003a; 2003b). Alexander and Lutfi (2004) have suggested that the poor performance of some listeners in the presence of a fixed-frequency ten-tone masker may reflect a perceptual grouping effect similar to that described by Kidd *et al.* (1994; 2001; 2002) in variable masker conditions. Alternatively, uncertainty might be required to produce informational masking as the CoRE model suggests, but the source of the uncertainty might not be in the acoustic stimulus. For example, uncertainty might be created by variability in the internal representation of the masker, or listeners might have an imperfect memory for the masker frequency. That infants are generally more susceptible than adults to informational masking in the absence of stimulus variability could be accounted for by immaturities in any or all of these mechanisms.

B. Masking in conditions of masker-frequency variability

Consistent with previous studies, masker-frequency variability had a detrimental effect on adults' detection performance (e.g., Neff and Green, 1987). However, the amount of informational masking measured for adults in the current study was larger than in previous studies of informational masking. For example, the average adult threshold ranged from 47.3 to 72.4 dB SPL in the current random two-tone condition whereas Neff and Dethlefs (1995) reported a threshold range of 5 to 64 dB SPL from their trained adult subjects using two-tone, random-frequency maskers. This could be due to the greater temporal variability in our experiment (discussed in Sec. C below).

Masker-frequency variability was clearly detrimental to infants as well as adults. Whether we judge infants to be more susceptible to masker-frequency variability than adults, however, depends on the comparison that is made. When the effect of masker-frequency variability is estimated as the elevation in threshold in the random two-tone relative to the broadband noise condition, the effect appears to be larger for infants than adults. Note that this comparison is the one used in most previous studies of informational masking, and infants' apparent increase in susceptibility to masking in the random two-tone condition is consistent with previous studies that have reported more masking for children than adults under conditions of masker-frequency variability (e.g., Allen and Wightman, 1995; Oh *et al.*, 2001; Wightman *et al.*, 2003). For example, thresholds for 7/8 preschoolers tested by Oh *et al.* (2001) in the presence of a random-frequency two-tone masker were elevated by 20 dB or more relative to thresholds for the same children in the presence of broadband noise. In contrast, none of the adults tested by Oh *et al.*

had higher thresholds in the random two-tone condition than in the broadband noise condition.

A different conclusion might be reached if the effect of varying the frequency content of the masker is estimated as the elevation in threshold in the random two-tone relative to the fixed two-tone masker condition. The increase in threshold associated with masker-frequency variability is similar for infants and adults in this comparison, providing no evidence that infants are more susceptible to masker-frequency variability than adults. Although only seven infants and ten adults were tested in both conditions, these differences are consistent across both infant and adult listeners. This finding raises an important question: What is the appropriate baseline condition for estimating the effect of masker-frequency variability? Effects of masker-frequency variability are often reported as the difference in threshold in the presence of a random-frequency multitone complex compared to that in broadband noise or to that in quiet. However, a logical reference for measuring effects of spectral variability is a masker that is matched to the random frequency masker in all respects except spectral variability. A single multitone masker sample approaches that condition (as in the minimal-uncertainty procedures discussed by Watson *et al.*, 1976). We are currently examining whether the effect of masker frequency variability is greater in children than in adults, when a fixed-frequency masker condition is the reference condition.

C. Limitations

The number of subjects tested in two masker conditions in this study was small and limited our ability to interpret these data. However, it is encouraging that the effects evident in between-group comparisons were also generally evident in the limited within-subject comparisons. The results indicate the questions that might be addressed in future studies employing a within-subjects design.

Infant-adult threshold differences are determined by age differences in sensitivity, in response bias and in the accuracy with which listener responses can be recorded. A particular limitation of the current study is the apparent difference in response bias between infants and adults. The age difference in threshold reported here likely underestimates the infant-adult difference in sensitivity. Psychometric functions have been reported for infants' and adults' detection of a 1000-Hz tone in continuous broadband noise using the current procedures (Bargones *et al.*, 1995). If the psychometric functions for infants and adults here are consistent with those of Bargones *et al.*, then the adult threshold would be 2 dB lower in each condition than reported here. However, given likely differences between the slope of the psychometric function for detection in a random-frequency masker and that for detection in a broadband noise masker (Durlach *et al.*, 2005; Lutfi *et al.*, 2003a) and the lack of psychometric function data for infants in any multitone masker condition, it is difficult to estimate the extent to which infants' thresholds differ from adults' in the two-tone masking conditions. Fortunately, response bias did not vary across masking conditions, making within-age-group comparisons meaningful.

A further limitation of these data is the possibility of an interaction between the spectral characteristics of the stimuli and the temporal variability inherent in our "infant" procedure. The observer-based procedure differs from most psychoacoustic procedures in the degree of temporal variability; that is, observations intervals are typically defined in psychoacoustic experiments, while in the observer-based procedure they are not. It is possible that this difference exacerbated the effects of spectral variability on masked thresholds. That thresholds for adults tested in the random two-tone condition were higher than reported in previous studies is consistent with this possibility. In a follow-up study conducted in our lab (Leibold and Werner, 2003), we attempted to separate the effects of temporal and spectral variability on adults' pure-tone detection. Five adults were tested using the same procedures described in the current study, except for the addition of a condition in which listeners initiated each trial, and a visual cue marked the masker burst with which the signal might coincide. For all listeners, performance was better when the listening interval was defined, with improvements in threshold of 10–20 dB. Because procedural differences apparently lead to only small differences in threshold for a 1000-Hz tone masked by broadband noise, these findings suggest a potentially interesting interaction between temporal and frequency variability, at least for adult listeners.

A third potential limitation of these data is that infants' thresholds in the random two-tone condition may have been constrained by a ceiling effect. The bulk of evidence does not indicate a ceiling effect. If this effect is present, however, infants' thresholds in the random two-tone condition would be higher than observed here, and the effects of spectral variability on infants' pure-tone detection greater than the current data would suggest.

V. SUMMARY AND CONCLUSIONS

Thresholds of both infants and adults were substantially elevated in the presence of a random-frequency masker. Whether there are developmental changes in the effect of spectral variability is a matter of interpretation and will only be settled by additional research. Infants, as predicted on the basis of previous studies, exhibited substantial masking in the presence of a fixed-frequency tonal masker. Adults also exhibited masking in the fixed-frequency tonal masker condition, although on average, not to the extent observed in infants. An argument can be made that this masking in the absence of spectral variability is informational masking. Finally, several observations suggest that the effects of spectral variability on detection interact with those of temporal variability. Understanding the development of listening abilities is challenging, but it may shed light on the mechanisms responsible for informational masking.

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[1]Given the wide frequency separation between the two masker components, masking by combination tones is not expected.

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