Effects of temporal uncertainty and temporal expectancy on infants' auditory sensitivity[a)]

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Adults are more sensitive to a sound if they know when the sound will occur. In the present experiment, the effects of temporal uncertainty and temporal expectancy on infants' and adults' detection of a 1 kHz tone in a broadband noise were examined. In one experiment, masked sensitivity was measured with an acoustic cue and without an acoustic cue to possible tone presentation times. Adults' sensitivity was greater for the cue than for the no-cue condition, while infants' sensitivity did not differ significantly between the cue and no-cue conditions. In a second experiment, the effect of temporal expectancy was investigated. The detection advantage for sounds occurring at an expected (most frequent) time, over sounds occurring at unexpected (less frequent) times, was examined. Both infants and adults detected a tone better when it occurred before or at an expected time following a cue than when it occurred at a later time. Thus, despite the fact that the auditory cue did not improve infants' sensitivity, it nonetheless provided the basis for temporal expectancies. Infants, like adults, are more sensitive to sounds that are consistent with temporal expectancy. © *2009 Acoustical Society of America.*. [DOI: 10.1121/1.3050254]

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I. INTRODUCTION

It is well established that infants have higher detection thresholds than adults (e.g., Schneider *et al.*, 1989; Bargones *et al.*, 1995; Berg and Boswell, 1999). Several contributors to infants' immature sensitivity have been suggested, including inattention and unselective listening across frequency (Bargones and Werner, 1994; Bargones *et al.*, 1995; Werner and Boike, 2001). Another possible contributor is unselective listening in time.

In a typical infant test procedure, the listener hears a continuous background noise that starts at the beginning of the test session. At certain points during the session the target tone is presented. There is no explicit cue informing the listener of when a tone might be presented, although the experimenter observing the listener's response is aware that a trial is in progress. The listener is thus uncertain about the timing of the signal tone. Temporal uncertainty is a feature of most, if not all, psychoacoustical procedures applied to infant listeners (e.g., Schneider and Trehub, 1985; Werner, 1995; Berg and Boswell, 1999).

It is generally accepted that adults listen selectively in time to optimize sensitivity. Temporal uncertainty reduces adults' auditory sensitivity (Egan *et al.*, 1961; Lappin and Disch, 1973; Lisper *et al.*, 1977). For example, Egan *et al.* (1961) examined listeners' ability to detect a tone in broadband noise when the time at which the tone could be presented was known and when the presentation time varied over intervals of 1–8 s. Their results showed that a signal that was detected with a d' of about 1.5, when presentation time was known, was detected with a d' of only 0.75 when the interval of uncertainty was 8 s. The results of Egan *et al.* (1961) indicate that such an increase in uncertainty would be equivalent to a 9 dB decrease in signal-to-noise ratio.

Another indication that adults listen selectively in time is that adult listeners detect tones better at expected presentation times than at unexpected presentation times (Leis Rossio, 1986; Chang, 1991; Chang and Viemeister, 1991). On a majority of trials in these studies, the signal occurred at a fixed time during the observation interval, the "expected" time. On the remaining trials, the signal occurred either before or after the expected time; these signals occurred at "unexpected" times. Leis Rossio (1986) measured adults' hit rate for a click in noise when the expected presentation time was 500 ms into the observation interval with unexpected presentation times varying between 100 and 1100 ms. A single-interval, yes-no procedure was used in that study. Chang (1991) and Chang and Viemeister (1991) used a two-interval forced-choice method and a 20 ms tone as a signal. Beside a visual indicator of each observation interval, a click was presented in the contralateral ear to indicate precisely the expected presentation time within the observation interval. Unexpected presentation times varied between 100 and 900 ms. Although the details of the procedures and the gradient of performance over time differed between the studies, both showed that as the presentation time of the signal deviated from the expected time, detection of the signal grew poorer. The results of these studies further support the benefit of knowing when to listen for a sound.

The effects of temporal uncertainty on detection have not been studied developmentally. If infants' detection is more disrupted by temporal uncertainty than adults', that

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could at least partially explain why infants' thresholds are higher than adults' in a temporally uncertain test procedure.

The effects of frequency uncertainty have been examined in children. Allen and Wightman (1995) found that children's detection was less affected than adults' by uncertainty about signal frequency, suggesting that children did not focus on a particular frequency when the signal frequency was known. Other results support the idea that infants do not listen selectively in frequency. For example, while adults detect tones at an expected frequency better than those at unexpected frequencies, infants detect expected and unexpected frequency tones equally well (Bargones and Werner, 1994). If infants do not focus on the time when signals are expected to occur, then decreasing temporal uncertainty may produce little change in infants' sensitivity. If that were the case, the difference between infants' and adults' sensitivity would be greater when temporal uncertainty is reduced, because adults' sensitivity would improve, but infants' would not.

The goal of the present experiments was to determine how infants' and adults' detection of a tone in noise is affected by temporal uncertainty and temporal expectancy in an infant test procedure. First, detection in the typical, temporally uncertain, infant procedure was compared to detection when a cue to the timing of signal presentation was provided. Second, detection of tones that occurred at expected times was compared to that of tones that occurred at unexpected times.

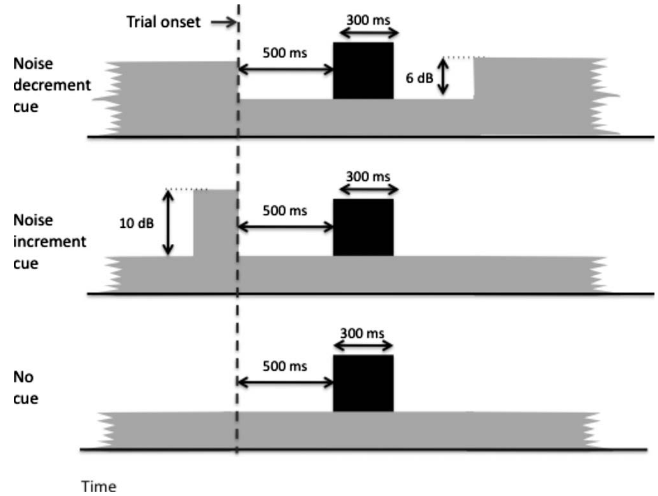

FIG. 1. Stimulus configurations in experiment 1. A broadband noise is presented continuously (gray shading). Tones (black rectangles) are presented on tone trials. In the no-cue condition (bottom panel), a tone is presented 500 ms after the observer starts the trial, with no indication to the listener that the trial is underway. In the noise-decrement cue condition, the spectrum level of the background noise drops from 26 to 20 dB SPL, 500 ms before the tone and remains at 20 dB for the duration of the trial. In the noise-increment cue condition, the spectrum level of the background noise increases from 20 to 30 dB for 200 ms, and then returns to 20 dB, 500 ms before the tone. The trial configurations on no-tone trials are the same as the tone trial in each condition, except that no tone is presented.

II. EXPERIMENT 1: EFFECTS OF TEMPORAL CUES ON SENSITIVITY

A. Method

1. Subjects

The data were provided by 98 infants and 93 adults. The age of the infants ranged from 29 to 40 wk (M=33.5 wk; SD=3.3 wk). The age of the adults ranged from 19 to 31 yr (M=24 yr; SD=3 yr). All subjects had normal hearing, as assessed by parent report or self-report. None had any risk factors associated with hearing loss, and all subjects passed screening typanometry on the test day. All infants were full term, healthy, and developing normally by parent report.

2. Stimuli

Subjects detected a 1 kHz tone, 300 ms in duration, with 16 ms rise and fall times, in the presence of a 2500 Hz low-pass noise. The noise was presented continuously throughout the session. The level of the tone was 50 dB Sound Pressure Level (SPL) for the infants and 42 dB SPL for the adults. The spectrum level of the noise was always 20 dB SPL during trials. These levels were chosen to allow detection of the tone with a $d'=1$, based on the results of a previous study (Bargones *et al.*, 1995).

In the cue conditions, the cue indicated when the trial began; when the tone was presented, its onset was at a fixed interval after the cue. The cues were always acoustic cues. Acoustic cues were chosen, because even young infants focus attention within a sensory modality and respond less to stimulation in a modality other than the one on which they are focused (Richards, 2000). Thus, it seemed preferable to present the cue in the same modality as the target stimulus. Two different cue conditions and a no-cue condition were tested. Each subject was tested in only one of these conditions. Data collection for one cue condition was completed before data collection for the other cue condition. To make sure that any effect of the cue type was not due to changes in testers or instrumentation, a separate group of listeners was tested in the no-cue condition for each cue condition.

The stimulus conditions are depicted in Fig. 1. In the noise-decrement-cue condition, a reduction in background noise level was the cue. The spectrum level of the noise was 26 dB SPL until trial onset. At trial onset, the spectrum level dropped to 20 dB SPL. When the tone was presented, its onset was 500 ms after trial onset. Thus, the cue was the drop in the level of the background noise. In the noise-increment-cue conditions, the cue to trial onset was a 200 ms, 10 dB increment in the background noise. When the tone was presented, its onset was 500 ms after the offset of the noise increment. In the corresponding no-cue conditions, no cue was presented to the listener to mark the onset of the trial, but when the tone was presented its onset was 500 ms after trial onset. Previous studies indicate that infants of this age can easily detect noise level changes of the magnitudes used in the noise cue conditions (Berg and Boswell, 1998; Werner and Boike, 2001).

Data collection in the noise-decrement-cue conditions was completed first. A noise decrement, rather than an increment, was chosen as the cue to ensure that the cue did not mask the signal tone. Subsequent work showed that forward masking of the tone by the cue would not be expected in this condition (Werner, 1999). An unexpected result in the noise-decrement-cue conditions led us to repeat the study using the noise-increment cue. The number of subjects tested in the noise-decrement cue, and no-cue conditions were 26 and 32, respectively, for the infants, and 28 and 25, respectively, for the adults. The number of subjects tested in the noise-increment cue, and no-cue conditions were 21 and 19, respectively, for the infants, and 20 and 20, respectively, for the adults.

The stimuli were presented to the subject's right ear using an Etymotic ER-1 insert earphone. A computer controlled the presentation of the stimulus and stored the results on each trial. Testing took place in a sound-attenuating booth.

3. Procedure

Infants' detection of the tone was measured using the observer-based psychoacoustic procedure (Werner, 1995). The infant, with ear tip in place, was seated on a parent's lap in the booth. An assistant, seated to the infant's left, manipulated toys on a table in front of the infant to maintain the infant's gaze forward. Both the parent and assistant listened to masking sounds over circumaural headphones so that they could not hear any of the sounds presented to the infant. Two mechanical toys in dark Plexiglas boxes with lights were placed to the infant's right; these toys were activated to reinforce the infants' response to the tone as described below. An observer watched the infant through a one-way window and on a video monitor. The observer pushed a button interfaced to the computer to begin a trial when the infant was quiet and attentive, without knowing whether a tone would be presented or not.[1] Both "tone trials" and "no-tone trials" were presented. Trials were 4 s in duration. If the observer judged on the basis of the infant's behavior that a tone had occurred, she pushed a button to indicate a "yes" response. If the observer was correct in judging that a tone had occurred, one of the mechanical toys in the test booth was illuminated and activated as reinforcement for the infant. The observer received feedback at the conclusion of all trials. The same general procedure was used to test adults. The adult subject was told to respond "when you hear the sound that will make the toy come on." An assistant outside the booth recorded the adult's responses, and a mechanical toy was activated when a response was recorded during a tone trial.

At the beginning of each session, a brief (approximately five trials) training phase was completed during which the tone was clearly audible and the reinforcer toy was turned on after every tone trial. This procedure demonstrated to the infant that the tone (or cue+tone) was associated with the toy. The toy was never turned on after no-tone (or cue alone) trials. In the second training phase, the tone remained clearly audible, tone and no-tone trials were equally probable, and the reinforcer toy only came on if the observer correctly identified a tone trial. The infant/observer team or the adult subject was required to achieve 80% correct on both tone and no-tone trials. Thus, in the cue conditions, the infant learned to respond to cue+tone, but not to the cue alone. Similarly, the observer learned to differentiate the infant's response to the cue+tone from the infant's response to the cue alone. This phase took about 22 trials to complete in all conditions. Once training criterion had been met, 35 test trials were presented, including 15 tone trials, 15 no-tone trials, and 5 probe trials. On probe trials, the level of the tone was chosen to be readily detectable, 51 dB SPL for adults and 60 dB SPL for infants. A subject's data were only used if at least three of the five probe tones were detected. This provided a check that the subject was "on task."

If a subject reached training criterion but did not complete all test trials, a new block of test trials was completed in a subsequent visit after an abbreviated training procedure.

Sensitivity was expressed as d'. Hit or false alarm rates of 1 or 0 were adjusted by $1/2n$ where n is the number of trials (Macmillan and Creelman, 2005). Levene's test of homogeneity of variance was significant in the dataset as a whole (with both infants and adults, $p<0.0001$), but it was not significant within age groups (both $p>0.4$). For that reason, the effect of the cues on d' was analyzed within age groups, and the pattern of effects compared between age groups.

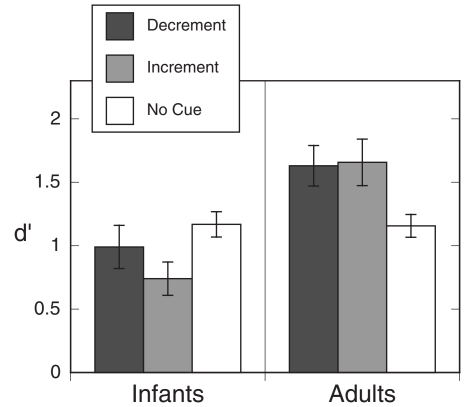

FIG. 2. Mean d' as a function of cue condition in experiment 1 for infants and adults, ± 1 SEM.

B. Results

In the no-cue conditions, both infants and adults generally achieved a d' around 1.0, as expected (e.g., Bargones *et al.*, 1995). Mean d' in the noise-decrement no-cue group was 1.28 (SD=0.83) for infants and 1.16 (SD=0.64) for adults; in the noise-increment no-cue group mean d' was 0.98 (SD =0.60) for infants and 1.15 (SD=0.70) for adults. The differences between the two no-cue groups were not statistically significant by t-test [$t(49)=1.4$, $p=0.17$, $d=0.4$) for infants; $t(43)=0.03$, $p=0.98$, $d=0.01$ for adults]. The data of the two no-cue groups were therefore pooled within age groups in the remainder of the analyses.

Average d' in the noise-decrement-cue (dark gray bars), noise-increment-cue (light gray bars), and no-cue (white bars) conditions is plotted in Fig. 2, with infants' data on the left and adults' data on the right. In each cue condition, adults' d' was greater than in the no-cue condition. One-way analysis of variance (ANOVA) indicated a significant effect of cue type (noise-decrement cue, noise-increment cue, no cue) for the adults [$F(2,90)=4.81$, $p=0.1$, $\eta^2=0.10$]. Bonferroni *post hoc* pairwise comparisons showed that d' was significantly higher in each of the cue conditions than in the no-cue condition (both $p<0.04$). The two cue conditions were not significantly different for adults ($p>0.99$).

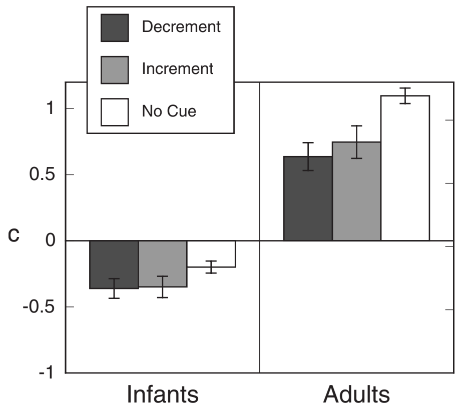

FIG. 3. Mean c as a function of cue condition in experiment 1 for infants and adults, ± 1 SEM.

Infants' d' in each cue condition, however, was actually a little lower than that in the no-cue condition; clearly neither cue improved infants' detection of the tone. For the infants, the effect of cue type was only marginally significant by one-way ANOVA $[F(2,95)=2.70,\ p=0.7,\ \eta^2=0.05)$ Bonferroni *post hoc* pairwise comparisons showed a marginally significant difference in d' between the noise-increment-cue and no-cue condition ($p=0.083$). The noise-decrement-cue and no-cue conditions were not statistically different ($p=0.55$), and the two cue conditions were not significantly different ($p>0.99$).

Adults are typically very conservative in their response bias in an "infant procedure," while infants/observers tend to be unbiased or a little liberal in their response bias in the same procedure (e.g., Werner and Marean, 1991). A cue might be expected to change response bias, although it is not clear that infants and adults would be affected in the same way. To examine the effect of the cue on response bias, bias was described as

$$c = 0.5[z(\text{hit rate}) + z(\text{false alarm rate})]$$

(Macmillan and Creelman, 2005). Hit or false alarm rates of 1 or 0 were adjusted by $1/2n$, where n is the number of trials. Positive values of c indicate a conservative bias, while negative values indicate a liberal bias. In the no-cue conditions, infants were somewhat liberal responders, while adults were quite conservative, as expected. Mean c in the noise-decrement no-cue group were -0.21 (SD=0.33) for infants and 1.05 (SD=0.39) for adults; in the noise-increment no-cue group -0.18 (SD=0.37) for infants and 1.15 (SD=0.37) for adults. The differences between the two no-cue groups were not statistically significant by t-test $[t(49)=-0.32,\ p=0.74,\ d=0.1$ for infants; $t(43)=-0.88,\ p=0.38,\ d=0.26$ for adults]. The data of the two groups were therefore pooled within age groups in the remainder of the analyses.

Average c in the noise-decrement-cue (dark gray bars), noise-increment-cue (light gray bars), and no-cue (white bars) conditions is plotted in Fig. 3, with infants' data plotted on the left and adults' data plotted on the right. As noted, infants tended to be a little liberal, while adults tended to be conservative. Both infants and adults tended to respond more liberally when a cue was provided, although the effect appears smaller for infants than for adults.

One-way cue-type ANOVA of c indicated a significant effect for adults $[F(2,90)=8.87,\ p=0.0003,\ \eta^2=0.16]$. Bonferroni *post hoc* pairwise comparisons indicated that both types of cues made adults significantly more liberal ($p<0.0001$ for noise-decrement cue, $p=0.025$ for noise-increment cue). For infants, the one-way cue-type ANOVA of c was marginally significant $[F(2,95)=0.246,\ p=0.09,\ \eta^2=0.05)$, but the Bonferroni *post hoc* pairwise comparisons were not significant ($p=0.173$ for noise-decrement cue, $p=0.305$ for noise increment cue). Thus, the cues clearly made adults more liberal in their response bias, and although infants' bias changed in the same direction with the cues, the effect was not statistically significant.

C. Discussion

The results of Experiment 1 indicate that a cue to trial onset led to improved performance in adult listeners, but not in infant listeners. For adults, this result held whether the cue was a decrement in the level of the background noise or an increment in the level of the background noise. Cue type also made little difference to infants, although some weak evidence suggested that the noise-increment cue could be detrimental to infants' performance.

As expected, adults' pure-tone detection was better when temporal uncertainty was reduced. This result is qualitatively consistent with previous reports (Egan *et al.*, 1961; Lappin and Disch, 1973; Lisper *et al.*, 1977).

The results for infant listeners suggest that infants do not benefit from a reduction in temporal uncertainty. It is possible that some other sort of cue might improve infants' detection performance. We avoided using a visual cue in the current experiments so that infants would not be required to divide attention between sensory modalities (e.g., Richards, 2000). However, a recent study suggests that visual information can facilitate infants' ability to separate an auditory target from a masker. Hollich *et al.* (2005) tested infant's ability to recognize a word in a background of competing speech. If the target word was paired with a video of a face saying the word, or even with an "oscilloscopelike trace" that was temporally synchronized with the word, infants recognized the word at a lower signal-to-background ratio than they did when no visual information was provided, or if the visual display was not synchronized with the target word. This suggests that a visual cue could improve infants' detection of a tone, even if an auditory cue does not.

To benefit from any cue, the listener must (1) learn that the cue predicts the possible occurrence of the signal, (2) learn and remember when the signal could occur following the cue, and (3) be able to listen selectively at the predicted time. One explanation for the cue's failure to improve infant's detection is that infants do not form expectancies that one event will follow another. Casual observation of infants suggests this is unlikely. Furthermore, it is well established that infants develop expectations that one visual event will follow another (e.g., Haith *et al.*, 1988). Another explanation is that while infants develop expectancies and attempt to direct listening to the appropriate time, their ability to estimate or to remember the interval between events is highly inaccurate. In that case, their uncertainty about the timing of the signal might not be reduced by a cue. A final explanation is that infants are not able to listen at a particular time for an expected event. That would be consistent with their listening along the frequency dimension: Infants detect expected and unexpected frequencies equally well, while adults detect expected frequencies better than unexpected frequencies (Bargones and Werner, 1994).

Experiment 2 was a more direct test of infants' ability to form and use temporal expectancies about sounds. The probe-signal method (e.g., Greenberg and Larkin, 1968; Scharf, 1987; Schlauch and Hafter, 1991; Dai and Wright, 1995; Arbogast and Kidd, 2000) was used to determine whether infants detect sounds presented at expected times better than they detect sounds presented at unexpected times. In this method, listeners detect a tone. On 75% of the trials, the tone is presented at one temporal position in the observation interval; on the remaining trials, the tone is presented before or after that time. The level of the tone is set so that it is detectable on, perhaps, 80% of the trials if it is presented at a fixed time. Adults detect the tone presented at the more common temporal position more often than they detect the tones at the other temporal positions (Leis Rossio, 1986; Chang, 1991; Chang and Viemeister, 1991), just as they detect tones at a more common frequency (e.g., Schlauch and Hafter, 1991), duration (Wright and Dai, 1994; Dai and Wright, 1995), or spatial position (Arbogast and Kidd, 2000) more often than they detect tones at other frequencies, durations, or spatial positions. We have previously used the probe-signal method to examine infants' "listening bands" in frequency (Bargones and Werner, 1994). We refer to the effect of temporally selective listening as a "listening window."

III. EXPERIMENT 2: PROBE-SIGNAL STUDY OF TEMPORAL SELECTIVITY

A. Method

1. Subjects

The final sample included 14 28–36 wk old infants and 19 18–30 yr old adults. The average age of infants was 35.5 wk (SD=2.2 wk). The average age of adults was 22.3 yr (SD=2.8 yr). The inclusion criteria were the same as for experiment 1. Sixteen other infants met the training criteria, but did not provide a complete data set in three visits to the laboratory. Fifteen infants did not meet training criteria. Four adults were excluded because they did not provide a complete data set in a 1 h test session. The high exclusion rate reflects the difficulties of this paradigm, in which the detectability of the stimulus must be controlled for each subject individually. If it takes several attempts to find an appropriate test level for an infant, time and patience often run out before all data have been obtained.

2. Stimuli

The stimuli were a 1 kHz tone and a broadband noise low-pass filtered at 2500 Hz. The duration of the tone was 150 ms, with 15 ms rise and fall times. The noise was presented continuously at a spectrum level of 30 dB SPL. The 10 dB noise increment used as a cue in experiment 2 was used to mark the beginning of an observation interval. On signal trials, the tone was presented either 200, 500, or 800 ms following the offset of the cue. The level of the tone was set for each listener to produce a correct detection rate of 70%–85%.

The duration of the tone burst is much longer than the stimuli used in previous studies of adults' listening windows (20 ms, Chang, 1991; 0.5 ms, Leis Rossio, 1986). A short-duration stimulus is desirable to obtain a narrow listening window. The longer duration was chosen, because infants' thresholds for short-duration sounds tend to be relatively worse, compared to adults, than their thresholds for a longer duration sound (Bargones *et al.*, 1995; Berg and Boswell, 1995). Thus, for this first attempt to examine temporal selectivity, we sacrificed precise estimation of the duration of the listening window to be able to obtain reasonable data from infants. Moreover, pilot testing indicated that adults demonstrated temporal selectivity with the 150 ms tone.

3. Procedure

The observer-based procedure was used to obtain these data, as in the earlier experiment. Each subject was tested in two conditions. In the "fixed" condition, the tone was presented at the same presentation time on all trials, either 200, 500, or 800 ms following the cue. Presumably, the assigned presentation time would be the expected presentation time in this condition. Subsequently, in the "mixed" condition, the tone was presented at 500 ms on 75% of the trials, at 200 ms on 12.5% of the trials, and at 800 ms on 12.5% of the trials. In this condition, the 500 ms presentation time is presumably the expected time and the other times, unexpected. If listeners are temporally selective, each of the presentation times should be detected equally well in the fixed conditions. In the mixed condition, tones presented at the unexpected times should not be detected as well as the tone at the expected time, and tones at the unexpected times should not be detected as well as tones presented at the same times in the fixed condition. Although there are no comparable data on temporal expectancy, several papers that have examined the effect of frequency expectancy have demonstrated that expectancy is built up quickly and is relatively robust with respect to the proportions of expected and unexpected frequencies in the mixed block (e.g., Scharf, 1987). Pilot testing with adults in our laboratory indicated that the same is true of temporal expectancy.

The training procedure was the same as in experiment 1. The level of the tone during training was 70 dB SPL for infants and 60 dB SPL for adults. The training procedure was completed twice, prior to testing in each condition. The presentation time in training matched that in testing in the fixed condition; in the mixed condition, the presentation time in training was 500 ms for all subjects.

The fixed condition was tested first. The purpose of the fixed condition was, first, to identify a tone level that the subject could detect 70%–85% of the time, and second, to assess performance when the tone was only presented at one of the three presentation times used in the mixed condition (i.e., when each was the expected time). Each subject was randomly assigned to the 200, 500, or 800 ms fixed presentation time condition. After reaching the training criterion of at least 80% correct, the listener completed a block of 32 test trials, with equal numbers of tone and no-tone trials. In the initial test block, the level of the tone was set at 62 dB SPL for the infants and at 49 dB for the adults. These levels were chosen on the basis of performance with the noise-increment cue in experiment 1. Fixed test blocks were repeated, adjusting the tone level as needed, until a level was identified at which the listener achieved a hit rate between 70% and 85% and a false alarm rate of no more than 40% on the test block. The average intensity levels used for infants and adults were 64.1 dB (SD=0.52 dB) and 48.8 dB (SD=1.0 dB), respectively.

In the mixed condition, the listener completed another training phase, with a presentation time of 500 ms. After reaching the training criterion of 80% correct, the listener completed a block of 32 test trials. The block contained 16 no-tone trials, 12 tone trials with a 500 ms presentation time, 2 tone trials with a 200 ms presentation time, and 2 tone trials with an 800 ms presentation time. The level of the tone was the level identified in the fixed condition as yielding a hit rate between 70% and 85% and a false alarm rate no greater than 40%. If the listener did not reach training criterion, training was reattempted in the next session. If the listener's false alarm rate was greater than 40% in the mixed test block, the same block was retested in subsequent sessions.

Whenever a fixed or mixed test block was repeated, the listener was given a few reminder trials prior to beginning the testing phase in subsequent test sessions. Adults completed all conditions in one 1 h session. Infants were scheduled for three sessions; a few infants required a fourth session to complete all conditions. Typically, an infant who did not complete all conditions in three sessions was excluded from the study.

The observer-based method used to test listeners in this study is a single-interval procedure. Single-interval procedures have been used in probe-signal experiments (e.g., Greenberg and Larkin, 1968) and other studies of the effects of uncertainty on detection (e.g., Richards and Neff, 2004; Scharf *et al.*, 2007). When the frequency of the signal varies in a block of trials, false alarm rate cannot be estimated independently for each signal, because it is not clear which no-signal trials should be assigned to each signal. In some cases (e.g., Greenberg and Larkin, 1968), hit rate has been used as the metric of performance for that reason. In the course of data collection in this experiment, hit rate was used as the primary performance measure. However, preliminary analyses revealed apparent differences in response bias that could influence the interpretation of the results. Infants had higher false alarm rates than adults (infants M=0.31, SD =0.06; adults M=0.07, SD=0.08). For that reason, d' was analyzed rather than hit rate. Hit or false alarm rates of 1 or 0 were corrected to $1-1/2n$ or $1/2n$, respectively, where n is the number of trials contributing to the rate (Macmillan and Creelman, 2005).

Two issues arise in the application of d' in this context. As discussed above, the first is the calculation of d' in the mixed condition, in which the temporal position of the signal in the observation interval varied within a block of trials. We calculated d' following the approach of Macmillan and Creelman (2005) using a single composite false alarm rate. This method has been shown to produce estimates of d' similar to those estimated with separate false alarm rates for each signal or in a two-alternative forced-choice procedure (Richards and Neff, 2004; Scharf *et al.*, 2007).

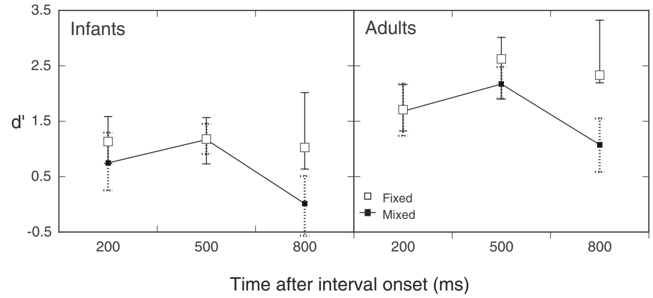

FIG. 4. Group d' as a function of presentation time in experiment 2 for infants and adults. The filled symbols represent the mixed condition; the unfilled symbols represent the fixed condition. The error bars represent the 95% confidence interval calculated using a procedure described by Miller (1996).

The second issue is the calculation of d' for individual listeners in different conditions, because the number of trials was very small. Small n would increase variability and statistical bias in d' estimates. More importantly, because the number of signal trials at unexpected times was, of necessity, much smaller than that at expected times, the maximum achievable hit rate in the unexpected conditions, after correction for rates of 0 or 1, would be much smaller than that in the expected condition. Consequently, d' would be lower in the unexpected than in the expected condition on that basis alone. Macmillan and Creelman (2005) recommended calculating d' for the group, essentially calculating d' from the average hit and false alarm rates in each condition, when the number of trials is small. This procedure has the additional advantage, in this case, of reducing the potential bias in the estimate of d' in the unexpected conditions, because the difference between the maximum hit rates in the unexpected and expected conditions would be much smaller, and because the average hit rates are not near the maximum. One value of d' was obtained, using the average hit and false alarm rate, for each age × presentation time × condition (fixed versus mixed) combination. These are referred to as group d'. To allow comparison of group d' between conditions, 95% confidence intervals around each d' were calculated using the exact calculation method described by Miller (1996) (see also Macmillan and Creelman, 2005, Chap. 13).[2] When this method is used, the size of the confidence interval above d' could differ from that below d'. Two group d' were considered different if the 95% confidence intervals did not overlap.[3]

B. Results

Figure 4 shows group d' as a function of presentation time, in the fixed (unfilled symbols) and mixed (filled symbols) conditions, for infants (left panel) and adults (right panel). The 95% confidence intervals in the fixed condition are drawn as dashed lines, while those in the mixed condition are drawn as solid lines. Each subject contributed to the data at all presentation times in the mixed condition, but each subject contributed to the data at only one presentation time in the fixed condition. It is clear that adults were more sensitive to the tone than the infants were in all conditions, although the age groups had equivalent hit rates (infants M =0.76, SD=0.04; adults M=0.78, SD=0.04) in the fixed condition. The important question here, however, was not the age difference in sensitivity, but the effect of presentation time on sensitivity within age groups.

As Fig. 4 indicates, infants and adults showed similar patterns of sensitivity across presentation times in the mixed condition, with apparently higher group d' at the expected 500 ms presentation time than at either 200 or 800 ms unexpected presentation times. Judging from the overlap in confidence intervals, group d' was higher at the 500 ms presentation time than at the 800 ms presentation time in the mixed condition. However, by the same criterion, group d' was not significantly higher at the 500 ms presentation time than at the 200 ms presentation time. Thus, it appears that both infants and adults were significantly more sensitive to a tone that occurred at an expected time than to a tone that occurred at a later unexpected time.

Interpretation of the effects of temporal expectancy depends on the idea that the signal is equally detectable when it is presented at any of the possible presentation times alone (i.e., when it is expected). Thus, it is important to verify that presentation time did not significantly affect sensitivity in the fixed condition. For infants, group d' was about the same when the fixed signal was presented at any of the temporal positions, and the confidence interval (solid lines) at each presentation time overlapped with those at the others. For adults, on the other hand, it appears that group d' is somewhat lower in the fixed condition when presentation time was 200 ms. (Although adults' hit rate was about the same at all presentation times, their false alarm rate was somewhat higher at the 200 ms presentation time.) The confidence interval around group d' at 200 ms overlaps with that at 500 ms, but not with that at 800 ms. Thus, adults were somewhat less sensitive to the signal when it was presented only at 200 ms than they were when it was presented at 800 ms. More importantly, however, they were no more sensitive to the signal when it was presented at 500 ms than they were when it was presented at either of the other times.

Finally, if the listener is more sensitive to the tone at an expected time than at an unexpected time, d' should be higher in the fixed condition than in the mixed condition for the mixed-condition-unexpected presentation times (200 and 800 ms), and d' should be the same in the fixed and mixed conditions for the mixed-condition-expected time (500 ms). In both age groups, it appears that sensitivity to the tones presented 200 or 500 ms after the cue was about the same in the fixed and mixed conditions, but that it was poorer in the mixed condition than in the fixed condition at 800 ms.

Thus, both age groups detected sounds that occurred before the expected presentation time as well as they detected sounds that occurred at the expected presentation time. They detected sounds that occurred after the expected presentation time more poorly than they detected sounds at the expected presentation time.

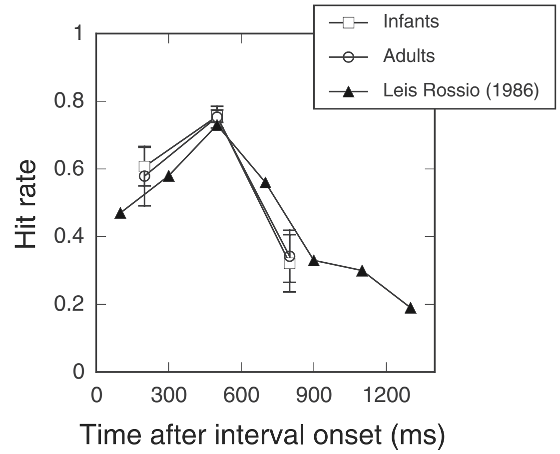

FIG. 5. Hit rate as a function of presentation time in experiment 2 compared to results of Leis Rossio (1986). Mean hit rate ±1 SEM is plotted for infants (squares) and adults (circles). Mean hit rate is plotted for adults tested by Leis Rossio's (1986) (triangles).

C. Discussion

The most notable result of experiment 2 was that infants and adults are similar in their auditory temporal selectivity. Infants, like adults, detect sounds at (and earlier than) an expected time better than they detect sounds at later times. In fact, this effect was remarkably similar in infants and adults in both its size and its dependence on presentation time.

Two previous studies have examined listening windows in adult listeners. In general, the current results are similar to those reported in those two studies. Figure 5 compares the results of Leis Rossio (1986) to those of the current experiment; Leis Rossio (1986) reported hit rate. The current results and those of Leis Rossio (1986) are similar, despite the fact that the signal duration was much longer in the current study and that the subjects in the current study received relatively little training and completed fewer trials. Thus, the listening window effect appears to be relatively robust with respect to variations in stimulus duration and some procedural details. Chang's (1991) results are plotted with the current results in Fig. 6; Chang (1991) reported d'. Note that the decrease in d' when the signal occurs at a time that is later than the expected presentation time is very similar in these and Chang's (1991) results. However, Chang's (1991) subjects show a much steeper drop-off in performance for unexpected presentation times that precede the expected time. Recall that in Chang's (1991) study a contralateral click was presented to indicate the expected presentation time within the observation interval; thus, in that study the subject would not be required to remember the expected presentation time from trial to trial. It is possible that in the absence of the contralateral click used by Chang (1991) to indicate the expected presentation time, listeners open their listening window earlier in the observation interval.

The conditions used in this experiment—long tones and three widely spaced presentation times—do not allow the

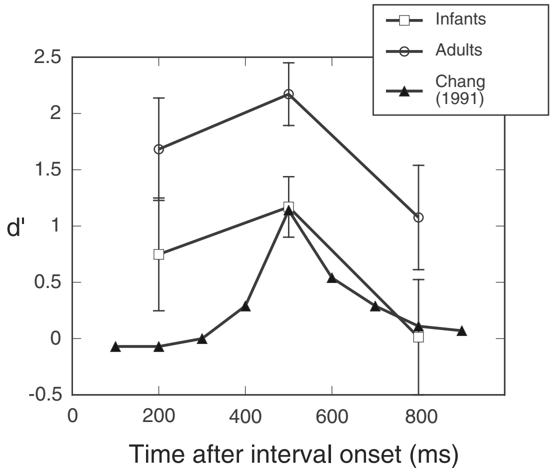

FIG. 6. d' as a function of presentation time in experiment 2 compared to results of Chang (1991). Group d' with 95% confidence interval is plotted for infants (squares) and adults (circles). Mean d' is plotted for adults tested by Chang (1991) (triangles).

duration of the listening window to be precisely estimated for either infants or adults. It may be that infants are broadly similar to adults in the ability to listen selectively in time but still have longer listening windows.

IV. GENERAL DISCUSSION

Infants' ability to listen selectively in time may seem surprising, given their failure to listen selectively in the frequency dimension, as measured using the probe-signal method (Bargones and Werner, 1994), as well as their failure to detect sounds more often when provided with a temporal cue in experiment 1. However, consideration of the literature on the development of visual expectancies makes this finding seem less surprising. In a long series of studies, Haith and co-workers demonstrated that if infants are presented with a series of pictures that occur in different, but predictable locations, infants will quickly begin to look at the expected location of the next picture in the series before the next picture is presented (e.g., Haith *et al.*, 1988; Haith, 1990; Adler and Haith, 2003). In fact, the infants in these studies were 3 months old, younger than the infants tested in the current studies. These studies, among others, suggest that infants develop expectancies about events and that their looking behavior reflects those expectancies. Because the auditory system begins to function prior to the visual system during early development and because auditory function is generally more mature than visual function at any point during development, one would expect infants' ability to use auditory information to be more mature than their ability to use visual information. Thus, the current findings are consistent with the findings of studies of visual development.

The experiment on temporal expectancy indicates that infants can listen selectively in time, but the experiment on cuing effects indicates that a cue does not improve infants' sensitivity. How can these two observations be reconciled? If infants are listening selectively for the tone at the expected time, why does the cue not improve their detection of the tone? No definitive answer to that question is possible on the basis of the current results. We might speculate that the cue has counteractive positive and negative effects on infants' detection. Knowing when to listen would have a positive effect on sensitivity. Three possible negative effects are (1) masking, (2) observer difficulty in distinguishing cue-alone from cue+tone trials, and (3) a type of "distraction" or informational masking.

Werner (1999) reported no forward masking of a short-duration tone by a broadband noise at a masker-tone interval of 200 ms among 6 month old listeners. Thus, it is unlikely that the noise increment would mask a longer duration tone presented 500 ms later. Clearly, the noise-decrement cue could not have forward-masked the tone. If the higher level of the background noise in the noise-decrement cue condition led to neural adaptation, detection of a signal in the period just after the noise level decreased could be difficult, but probably not for 500 ms. Thus, it is unlikely that a sensory masking effect is negatively affecting infant detection in the cue conditions.

Another possibility is that the cue led to a change in the infants' behavior that made it difficult for the observer to distinguish cue-alone trials from cue+tone trials. If, for example, the infant made a clear response to the cue on every trial, that response may have obscured any response to the tone. Recall, however, that the infant/observer team reached a training criterion of 80% correct in both the cue and no-cue conditions. Similarly, on probe trials during the testing phase, the infant/observer team achieved an average hit rate of about 86% in both cue and no-cue conditions.[4] That means that the observer was able to distinguish cue-alone and cue+tone trials reliably, at least when the tone was clearly audible to the infant. Furthermore, the number of trials required to reach training criterion was no different in the cue and no-cue conditions. Is it possible that the infants' response to the tone became less salient when the level of the tone was reduced to near-threshold level? Although that possibility cannot be dismissed, observers, anecdotally, do not report a strong correlation between the salience of the infants' response and the level of the stimulus. Moreover, while infant/observer response bias tended to be somewhat more liberal in the cue conditions, that tendency was not statistically significant. An increase in yes responses during testing would be expected, if the observer were responding on the basis of the infant's response to the cue. Of course, it is still possible that the observer's response bias changed over the course of testing, if the infant's response became an unreliable indicator of cue+tone trials. Thus, while we do not believe that the negative effect of the cue on infants' sensitivity results from the methodology used to measure infants' sensitivity, we cannot eliminate the possibility.

Informational masking has been defined as masking that cannot be explained in terms of peripheral, "energetic," masking (e.g., Durlach *et al.*, 2003). Informational masking can be demonstrated in many adults when the masker frequency is randomly varied over presentations (e.g., Neff and Green, 1987), and in infants and young children even when the masker does not vary in frequency (Leibold and Neff, 2007; Leibold and Werner, 2007). In adults, informational masking is not reported for forward maskers (Neff, 1991), and as previously noted, Werner (1999) reported no forward masking among 6 month old listeners at a 200 ms masker-tone interval. However, Werner (1999) presented the forward masker and tone several times on each trial, while in the current experiment the tone was presented only once on each trial. It may be that the repeated tone reduced informational masking for the infants in the forward masking experiment (e.g., Kidd *et al.*, 1994). Furthermore, infants and children exhibit informational masking under conditions that do not produce a similar effect in adults (e.g., Werner and Bargones, 1991; Leibold and Neff, 2007; Leibold and Werner, 2007). Thus, the informational masking explanation remains tenable.

The development of frequency selective listening provides an interesting contrast to that of temporally selective listening. Infants and children's pure-tone threshold is higher when other sounds, remote in frequency from the target tone, are presented simultaneously with the tone (e.g., Werner and Bargones, 1991; Leibold and Neff, 2007; Leibold and Werner, 2007). It has been argued that this sort of informational masking is related to a lack of frequency selective listening, as demonstrated in a probe-signal procedure (Bargones and Werner, 1994). That infants' thresholds are affected by remote frequency sounds seems consistent with the idea that infants listen broadly across frequency, even for a narrowband sound. In the temporal domain, it appears that infants can listen selectively for a sound at a specific time. It would be interesting should it prove that they are nonetheless "distracted" by temporally remote sounds.

To return to the question posed at the beginning of this paper, do the effects of temporal uncertainty contribute to the age differences in threshold typically observed in an infant psychoacoustics task? On the basis of the results of experiment 2, the answer would be "no."

V. SUMMARY AND CONCLUSIONS

Providing listeners with an auditory cue indicating the beginning of the observation interval improves adults' tone detection in noise, but not infants'. This pattern of results is observed whether the cue is a decrement in the noise level or a brief increment in the noise level. At the same time, infants, like adults, are more likely to detect a tone that follows the cue by an expected interval than by a longer unexpected interval. Thus, despite the fact that the auditory cue does not increase infants' detection efficiency, it appears that infants develop expectancies about when the signal tone will occur relative to the cue and that these expectancies guide infants' listening. Both infants and adults listen selectively in time.

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[1]Both the noise increment and the noise decrement began as soon as the observer pushed the button to start a trial. Because the trial actually began with the offset of the noise increment, the delay between the button press and the tone, if it occurred, was 200 ms longer in the noise-increment condition. The performance of a separate group of subjects tested with a 200 ms interval between the offset of the noise increment and the onset of the tone, however, did not differ from that of either group of subjects tested with a 500 ms trial-onset-signal interval.

[2]The calculation of confidence intervals around d' assumes that the outcome on each trial is independent of that on other trials. Our data violate that assumption in the sense that multiple trials come from each subject. However, the violation of this assumption is likely to have a small effect on the calculation of confidence intervals, compared to the potential bias in d' calculation that results from differences in the number of trials available at each presentation time for individual subjects in the mixed condition.

[3]In a parallel analysis, d' was calculated for each subject in each condition, and differences in mean d' were assessed using separate analyses of variance for infants and adults. The results of these analyses were the same as those reported for the group d' analysis, except that for both infants and adults, group d' in the mixed condition at the 200 ms presentation time was significantly better than that at the 800 ms presentation time. This difference would not have influenced interpretation of the results.

[4]Infants' hit rate on probe trials averaged 0.86 (SD=0.16) for the noise-decrement cue, 0.86 (SD=0.17) for the noise-increment cue, and 0.87 (SD=0.15) for no cue. The differences between these means was not statistically significant by one-way ANOVA [$F(2,95)=0.03, p=0.97$].

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