Forward masking among infant and adult listeners

Lynne A. Werner
Department of Speech and Hearing Sciences, University of Washington, 1417 N.E. 42nd Street, Seattle, Washington 98105-6246

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Psychophysical forward-masked thresholds were estimated for 3- and 6-month-old infants and for adults. Listeners detected a repeated 1000-Hz probe, with 16-ms rise time, no steady-state duration, and 16-ms fall time. Unmasked thresholds were determined for one group of listeners who were trained to respond when they heard the probe but not at other times. In the masking conditions, each tone burst was preceded by a 100-ms broadband noise masker at 65 dB SPL. Listeners were trained to respond when they heard the probe and masker, but not when they heard the masker alone. The masker–probe interval, Δt, was either 5, 10, 25, or 200 ms. Four groups of subjects listened in the masked conditions, each at one value of Δt. Each listener attempted to complete a block of 32 trials including four probe levels chosen to span the range of expected thresholds. ''Group'' thresholds, based on average psychometric functions, as well as thresholds for individual listeners, were estimated. Both group and individual thresholds declined with Δt, as expected, for both infants and adults. Infants' masked thresholds were higher than those of adults, and comparison of masked to unmasked thresholds suggested that infants demonstrate more forward masking than adults, particularly at short Δt. Forward masking appeared to have greater effects on 3-month-olds' detection than on either 6-month-olds' or adults'. Compared to adults, 6-month-olds demonstrated more forward masking only for Δt of 5 ms. Thus, susceptibility to forward masking may be nearly mature by 6 months of age. © *1999 Acoustical Society of America.* [S0001-4966(99)00704-3]

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INTRODUCTION

The purpose of the experiment reported here was to examine the development of recovery from adaptation, as measured by thresholds under forward masking. Adaptation is one of several mechanisms believed to limit temporal resolution, the ability to follow amplitude changes in a sound over time. Immaturity of susceptibility to adaptation has been proposed as an explanation of age-related changes in temporal resolution.

Several studies indicate that temporal resolution undergoes development during infancy and childhood. Irwin *et al.* (1985) first reported that children's ability to detect temporal interruptions, or gaps, in a low-frequency noise band did not mature until 10 years of age. Only slight improvements in gap detection in high-frequency noise bands were observed between 6 years and adulthood. Wightman *et al.* (1989) subsequently reported that gap detection was immature among 3- and 4-year-old children, but mature by age 5 years for noise bands centered at both 400 and 2000 Hz. Werner *et al.* (1992) found that gap detection was very poor among 3-, 6-, and 12-month-old infants. Studies of duration discrimination among infants and 4–10-year-olds (Elfenbein, Small, and Davis, 1993; Jensen and Neff, 1993; Morrongiello and Trehub, 1987) reported similar age-related improvements in performance. By 6 years of age, many children in these studies could discriminate between sounds of different durations as well as adults could.

Although age-related change in measures of temporal resolution has been documented, the mechanisms responsible for that change are unknown. A listener's ability to follow a sound's amplitude envelope is actually limited by several underlying mechanisms. In order to accurately encode the amplitude envelope, the time of occurrence of amplitude peaks must be accurately represented in the pattern of neural discharges. This ability is the one most closely identified with temporal resolution. Encoding the amplitude envelope, however, also requires precise intensity resolution: The neural response must change sufficiently with a change in sound amplitude for the difference in amplitude to be detectable. Furthermore, the neural representation of the amplitude envelope will be affected by adaptation, the process that is responsible for the rapid reduction in primary neural response rate that occurs just after sound onset, and for a reduction in sensitivity that occurs following offset of a sound. Finally, even frequency resolution may theoretically be involved in temporal resolution insofar as narrow filters ''ring'' for a longer time period than broad filters do. Immaturity in any of these underlying mechanisms could contribute to immature perception of temporal modulations of sound.

The development of three of the four mechanisms just described has been examined. There is growing evidence that temporal coding is mature before gap-detection thresholds (Hall and Grose, 1994; Levi and Werner, 1995, 1996), although whether temporal coding is immature in early infancy is unsettled (Levi, Folsom, and Dobie, 1993, 1995; Levi and Werner, 1996). Intensity coding, however, may develop over a time course similar to that seen for gap detection: Intensity discrimination is immature until 5 or 6 years of age (Jensen and Neff, 1993; Maxon and Hochberg, 1982; Sinnott and Aslin, 1985). Frequency resolution is only immature at high frequencies at 3 months of age and is mature by 6 months of age (Hall and Grose, 1991; Olsho, 1985; Schneider, Morrongiello, and Trehub, 1990; Spetner and Olsho, 1990).[1]

Trehub, Schneider, and Henderson (1995) have suggested recently that infants and children are better at detecting gaps in very short duration sounds than they are at detecting gaps in very long duration sounds, because they are more susceptible to adaptation effects than adults. Evoked potential rate-effect studies suggest, in fact, that the time required to recover from prior stimulation is longer for infants and children than it is for adults, and the time required to recover from prior stimulation has been shown to be directly related to susceptibility to adaptation in single-unit studies (e.g., Harris and Dallos, 1979). Increasing the rate of stimulus presentation has a greater effect on the auditory brainstem response (ABR) among infants younger than 3 months of age than it does on adults' ABR (Dey-Sigman, Ruth, and Rubel, 1984; Fujikawa and Weber, 1977; Lasky, 1984), and immature, pronounced rate effects for middle- and long-latency evoked potentials are reported well into childhood (Hall, 1992; Jerger *et al.*, 1987; Kraus *et al.*, 1985). Along the same lines, Lasky (1991, 1993) reported that newborns' click-evoked ABRs are more affected by a forward masker than are those of adults.

Forward masking is thought of as a psychophysical measure of adaptation in the auditory system. The relationship between masker–probe delay and the probe's threshold is an indication of the time course of the auditory system's recovery from prior stimulation. The precise locus and mechanism of forward masking are not completely understood (e.g., Shannon, 1990; Turner, Relkin, and Doucet, 1994), and under certain circumstances masker–probe confusions can elevate forward-masked thresholds (Neff, 1985). If, however, infants are more susceptible to adaptation than adults, we would expect that they would demonstrate more pronounced forward masking effects than adults.

I. METHOD

The probe was a 1000-Hz tone, with 16-ms rise and fall times and no steady-state duration. The masker was a broadband noise, 100 ms in duration, including 16-ms rise and fall times. Masker level was set at 65 dB SPL. A broadband noise masker was used to make sure that the masker and probe were distinct in sound quality, so that masker–probe confusions would be less likely (Neff, 1985). The masker–probe interval, Δt, was 5, 10, 25, or 200 ms, measured from the offset of the masker to the onset of the probe. The stimuli were presented to each listener's right ear through an Etymotic ER-1 insert earphone in a foam ear tip, trimmed as necessary to fit infant ear canals. Testing was carried out in a double-walled booth. The experiment was controlled by a computer.

The subjects were 114 3-month-old infants; 58 6-month-old infants; and 51 18–30-year-old adults. Infants were tested within 2 weeks of their 3-month or 6-month birthday. Adult age was taken as age at last birthday. All subjects passed a screening questionnaire assessing risk for hearing loss (Joint Committee on Infant Hearing, 1991), had neither been treated for otitis media within 2 weeks nor had more than two episodes of otitis media, and passed screening tympanometry at each laboratory visit. None had previously participated in a psychoacoustic study. An additional 49 3-month-olds and 21 6-month-olds were tested, but did not provide data because they responded inconsistently to the probe.

The number of infants who were tested but did not provide data is troublesome. It is not typical of published studies using similar methods, and no explanation for the high attrition rate is apparent. These data were collected after 2 years of pilot testing to optimize the details of the procedure; no procedural variant was successful in producing data from more infants than the one used in the final study. Four different individuals tested infants for this study over a period of 3 years. None was more successful than the others; the attrition rate did not decline with time or practice. The data obtained from adults compare as expected to those reported for well-trained listeners, arguing that a peculiarity of the stimuli was not responsible. No differences between infants who provided data and those who did not—in age or gender, for example—have been identified.

Despite the difficulties in interpretation resulting from the apparently select sample, I believe that the data presented here provide a meaningful representation of infants' auditory capacities for several reasons. First, these data are indistinguishable, in terms of variability and internal consistency, from data obtained in other tasks (e.g., detection in quiet, frequency discrimination, masked detection) for which a similar number of trials was obtained from each infant. Second, the infants who provided data in this study took no longer to meet training criteria than did infants who have provided data for other tasks. Third, comparison of the data of infants who provided complete data sets to those who provided partial data sets indicated little difference in level of performance.

Of course, it is impossible to know what the results would have been had the data of a higher proportion of infant subjects been included. It is unlikely, however, that the performance of the infants who were excluded would have been better than that of the infants who were included. Thus, it would be reasonable to think of the present results as establishing a lower limit on infants' threshold under forward masking; that is, it would be safe to say that infants are at least as bad at detecting tones under forward masking as indicated by the present results.

Initially, data collection concentrated on 3-month-olds and adults, and ten thresholds/condition were obtained at each age. When it became apparent that there was a large difference between 3-month-olds and adults, 6-month-olds were tested to see whether any age-related change in forward masking occurred during infancy. In the interest of timely dissemination, and because it was difficult to obtain these data, it was decided to obtain five thresholds/condition from 6-month-olds. Changes in the data analysis procedure after data collection was completed resulted in changes in the number of subjects contributing data at different ages and in different conditions.

Unmasked detection data were provided by 45 3-month-olds; 31 6-month-olds; and 10 adults. The data from infants were originally described by Werner and Marean (1991).

They were collected over the same time period as the masked-detection data, using the same methods, and were reanalyzed for comparison with the masked-detection data here. Some of these subjects provided as many as 60 test trials; all data obtained from a given subject were used in the present analysis. For masked detection, each subject listened at one value of Δt. The numbers of 3-month-olds providing data were 14, 16, 18, and 21 at Δt of 5, 10, 25, and 200 ms, respectively. The corresponding numbers of 6-month-olds were 5, 5, 7, and 10. For adults, the corresponding numbers were 11, 9, 8, and 13. Because of the small number of subjects tested at 6 months, the results for that age group must be interpreted cautiously.

Listeners heard two types of trials during the experiment, signal and no-signal trials. In the unmasked-detection condition, signal trials consisted of 20 repetitions of the probe with a 444-ms interstimulus interval. Unmasked no-signal trials were periods of equal duration during which no stimulus was presented. In masked-detection conditions, masker and probe were presented on signal trials, while only the masker was presented on no-signal trials. On signal trials, 20 repetitions of the sequence masker–Δt–probe were presented, with 344 ms between repetitions. On no-signal trials, 20 repetitions of the noise burst were presented, with interstimulus intervals of $372\,\text{ms}+\Delta t$. The interval between noise-burst onsets and the total trial duration were the same for masked signal and masked no-signal trials in each Δt condition. These long trials were used because 3-month-olds often have long response latencies.

The method used to assess infants' sensitivity was an observer-based procedure (Werner, 1995). The infant was seated on a parent's lap in the test booth, facing a window and a video camera. An assistant sat to the infant's left and manipulated quiet toys to keep the infant attending at midline. The parent and assistant listened to masking sounds to ensure that they could not hear any sound that was presented to the infant. Two mechanical toys with lights in a dark Plexiglass box were placed to the infant's right. An observer watched the infant though the window and on a video monitor. When the infant was quiet and attentive, the observer cued the computer to begin a trial. The observer did not know whether a signal or no-signal trial was being presented. Signal and no-signal trials were presented with equal probability. The observer decided, based on the infant's behavior, whether a signal or no-signal trial was being presented. If the observer correctly identified a signal trial before the trial ended, one of the mechanical toys in the booth was activated and illuminated to reinforce the infant's response. The observer received feedback after every trial. Infant responses typically include head or eye movements or changes in activity. Success in this procedure clearly depends on the infant's response to the probe and on the observer's ability to detect the infant's response, but if the observer can reliably identify signal trials, then the infant must be detecting the probe.

The infant/observer team was required to meet a criterion level of performance prior to data collection. Initially, the level of the probe was fixed at a value expected to be clearly audible to the listener, and the mechanical toy reinforcer was activated at the end of every signal trial. The purpose of this procedure was to demonstrate the association between the probe and the reinforcer to the infant. Once the infant/observer team had achieved four of five consecutive trials correct (hits or correct rejections), another series of trials was completed in which the probe was still clearly audible, but the reinforcer was only activated if the observer correctly identified a signal trial. This phase of the experiment continued until the infant/observer team had achieved four of the last five no-signal trials correct and four of the last five signal trials correct. The average number of trials required to complete the training procedure was 22.7 (s.d. $=8.1$) for 3-month-olds and 23.3 trials (s.d.$=9.3$) for 6-month-olds, with no differences across conditions.

The test phase of the experiment consisted of a block of 32 trials. On a signal trial, one of four probe levels was presented. The order of probe levels was randomized with the constraint that equal numbers of trials were completed at each level by the end of the 32 trials. The probe levels were evenly spaced over a 20-dB range and were chosen for each age group on the basis of pilot testing. In the 200-ms Δt condition, some infants were tested with a range of levels centered around the expected unmasked threshold, while others were tested with a range of levels centered 10 dB higher. The additional condition was added to ensure that the range of levels used did not strongly influence the threshold obtained.

Adults listened alone in the booth. They were told to respond whenever they heard ''the sound that makes the toy come on.'' Otherwise, the procedures were identical to those used with the infants. Adults nearly always completed the training procedure in the minimum possible number of trials and completed all test trials.

If an infant completed at least 30 test trials, an individual threshold estimate was attempted. At the time the data were collected, the plan was to exclude infants with false alarm rates greater than 0.25 or with nonmonotonic psychometric functions. It was subsequently decided to deal with high false alarm rate and nonmonotonic psychometric functions statistically rather than by exclusion. However, some infants had been retested and provided more than one block of test trials, because the false alarm rate was high or because performance was nonmonotonic with level in the first block completed. In such cases, all of the infant's data were used to estimate a single threshold. Psychometric functions of a form described by Green (1995) were fit to the data using a maximum likelihood criterion. The underlying relationship between level and the proportion of ''yes'' responses, p(''yes''), was assumed to be linear, but bounded by the false alarm rate and an upper ''asymptote.'' Given the small number of trials per subject, it was unlikely that the data would be better described by a more complex function. In fact, logistic and probit functions resulted in very similar threshold estimates, but far fewer successful fits than a linear function. The false alarm rate was estimated for each subject on the basis of responses on the 16 no-signal trials. The upper bound was taken as 0.86 for infants and as 0.97 for adults, values obtained by Bargones, Werner, and Marean (1995) using the same probe. Threshold was taken as the level at which p(''yes'')=0.6, the approximate midpoint of the infant psychometric function.

Thirty-nine unmasked thresholds and 58 masked thresholds (11–19 per condition) were obtained from 3-month-olds. Twenty-eight unmasked and 23 masked thresholds (3–11 per condition) were obtained from 6-month-olds. Ten unmasked and 49 masked thresholds (8–13 per condition) were obtained from adults. The subjects who provided data, but not thresholds, were evenly divided between those who completed fewer than 30 test trials and those who completed 30 test trials but for whom a threshold could not be estimated (psychometric function with negative or zero slope, fitting procedure would not converge).

A bias-free measure of sensitivity would be clearly preferable to p(''yes''), particularly because infants tend to have higher false alarm rates than adults do. However, in previous work we have found that the use of the parametric statistic d' may not be justified in observer-based studies of infant psychoacoustic performance (Werner, Kopyar, and Bargones, 1993), and it is unfortunate that no means for estimating a nonparametric bias-free sensitivity statistic were available in the laboratory at the time that these data were collected. Furthermore, when performance in this study was described in terms of d', the number of individual psychometric functions that could be successfully fit was reduced by 50%–70%. For those reasons, the decision was made to present the results in terms of p(''yes''). However, analysis in terms of d' yielded essentially the same results as those obtained using p(''yes''), and to provide the proper perspective, equivalent values of d' are reported in the text.

II. RESULTS

Because the number of trials obtained even from infants who completed the test procedure was small, the data were analyzed in two ways. First, ''group'' psychometric functions were constructed combining the data from all subjects of a given age in a given condition. Group psychometric functions have frequently been used in developmental studies where few data have been obtained from each subject (e.g., Trehub *et al.*, 1995). Group psychometric functions have the advantage of allowing us to use the data of any subject who completed even one test trial. Group psychometric functions have the limitation that they provide no information about variability in sensitivity across subjects, so individual thresholds were also estimated for as many infants as possible. Individual thresholds were only estimated for infants who completed at least 30 test trials. While the individual thresholds are based on few trials, they can be interpreted in light of the group thresholds, and they provide some information about the variability in sensitivity across subjects.

A. Group psychometric functions and thresholds

The data of all subjects who completed any test trials were used to construct group psychometric functions for each listening condition (masked detection at four values of Δt and unmasked detection). About 14% of the infants included completed fewer than 32 test trials; all of the adult

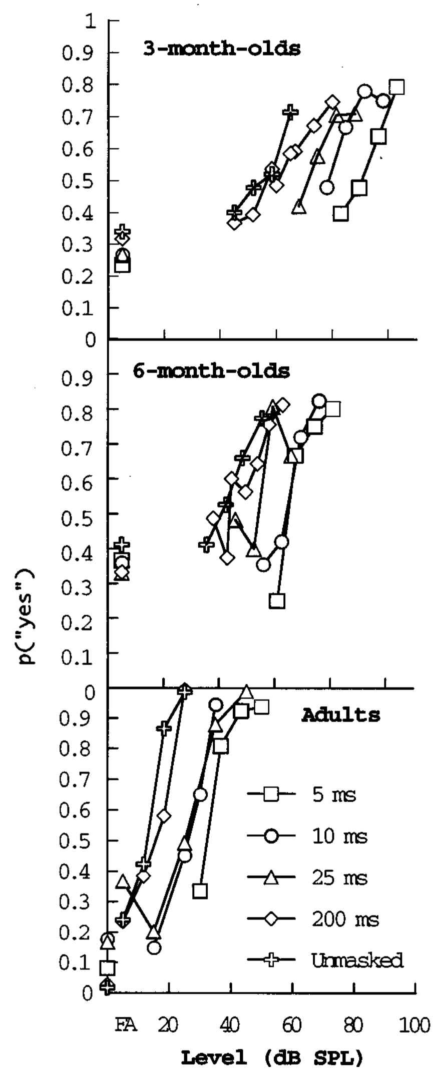

FIG. 1. Group psychometric functions for detection of unmasked and forward masked 1000-Hz tone pips, for three age groups. Points plotted over ''FA'' are false alarm rates.

subjects had complete data sets. For 3-month-olds, the percentages of trials included from incomplete data sets were 0, 5, 12, 8, and 8% for the masking conditions with Δt of 5, 10, 25, and 200 ms and the unmasked condition, respectively. The corresponding percentages for the 6-month-olds were 29, 15, 11, 7, and 8%. The proportion of ''yes'' responses recorded at each probe level and on no-signal trials across all subjects who completed test trials was calculated. These functions are shown in Fig. 1.

The proportion of ''yes'' responses increased with probe level more or less monotonically at all three ages and in all listening conditions. The functions of 6-month-olds had more nonmonotonic points than those of 3-month-olds or adults, but recall that there were fewer 6-month-old infants tested. Among 3-month-olds average p(''yes'') on no-signal trials, false alarms, ranged from 0.24–0.34. The false alarm rate of 6-month-olds was a little higher, 0.33–0.41. The adults' false alarm rates were 0.02–0.18 in masked detection and 0.01 in unmasked detection. These rates are typical of those generally observed for infants and adults in this procedure. On average, p(''yes'') at the highest level tested in

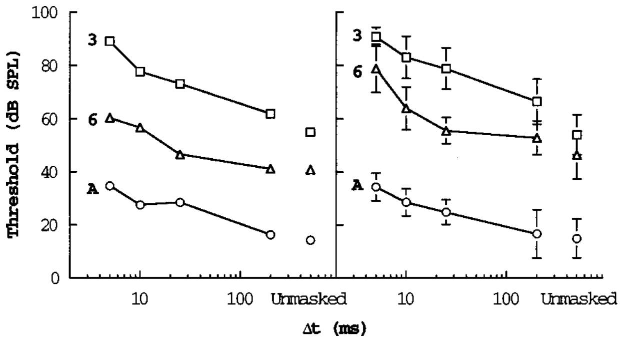

FIG. 2. Forward-masked threshold as a function of Δt for three age groups, calculated by two methods. Average thresholds estimated from the group psychometric functions are plotted in the left panel. Thresholds calculated for individual listeners are averaged and plotted in the right-hand panel. ''3'' indicates the data of 3-month-olds; ''6'' indicates the data of 6-month-olds; and ''A'' indicates the data of adults. Error bars indicate ± 1 sem. Unmasked thresholds are the points plotted to the right in each panel.

each condition was around 0.8 for the infants and 1.0 for the adults. That would mean that infants achieved an average d' of 1.0–1.6 at the highest level tested in each condition, while adults achieved an average d' between 2.5 and 3.9. Finally, notice that performance was poor among infants who were tested at lower levels in forward-masked detection at 200-ms Δt. These are the lowest four data points on the infants' functions for 200 ms. Thus, the shift in the group psychometric function to higher levels for masked detection in this condition is not simply a result of using a higher range of probe levels.

The group psychometric functions tend to shift to higher levels for masked detection than for unmasked detection, as expected. The functions also shift, more or less, to higher levels in masked detection as Δt decreases. From the spread of the psychometric functions, it appears that 3-month-olds' detection is affected by the forward masker more than adults' detection is.

The thresholds calculated from the group average psychometric functions will be referred to as ''group thresholds.'' To examine the age difference in forward masking quantitatively, a group threshold was calculated for each psychometric function. Threshold was taken as the level at which p(''yes'') was equal to 0.6, the approximate midpoint of the psychometric functions. This point was estimated by fitting a line by least-squares criterion to each psychometric function. The group thresholds obtained are plotted in Fig. 2 (left panel). In general, the 3-month-olds have higher group thresholds than the 6-month-olds who have higher group thresholds than the adults under all conditions.[2] The infant–adult difference is much larger than typically observed for long-duration tone detection. That result is consistent with previous observations from this laboratory (Werner and Marean, 1991; Bargones *et al.*, 1995), but is not understood. Berg and her colleagues (e.g., Berg, 1991, 1993; Berg and Boswell, 1995) have reported the same differences between 6-month-olds and adults in thresholds for short-duration sounds under several conditions. Because the focus of the current paper is on the effect of a forward masker on threshold, rather than on the absolute values of the thresholds, the reader interested in possible reasons for the large age differences in threshold is referred to those published papers.

It also appears that the difference between 3-month-olds' and adults' group thresholds is greater under forward masking than it is when the probe is unmasked; in fact, the difference between 3-month-olds' and adults' group thresholds increases progressively with decreasing Δt. These trends are not evident in the group-threshold difference between 6-month-olds and adults. The effect of introducing a forward masker and the decline of forward masking with increasing Δt seem quite similar for 6-month-olds and adults. At Δt of 200 ms, forward-masked threshold is about the same as unmasked threshold for 6-month-olds and for adults. For 3-month-olds, the masked-group threshold at 200 ms is about 5 dB higher than unmasked-group threshold. The same pattern is evident in thresholds calculated from group psychometric functions based on d' using a threshold criterion of $d' = 0.51$, equivalent to a hit rate of 0.6 and a false alarm rate of 0.4. The only difference was that the d' thresholds of the 6-month-olds tend to be about 6 dB closer to those of the 3-month-olds.

That masking appears to grow at a faster rate with decreasing Δt in the youngest listeners suggests that 3-month-olds are more susceptible to forward masking than adults are. Adults and 6-month-olds appear to be similar in their susceptibility to forward masking.

B. Individual thresholds

Psychometric functions were fit to the data of individual infants who completed at least 30 test trials, as described above. The average individual unmasked thresholds and masked thresholds as a function of Δt are shown in Fig. 2 (right panel). Most of the expected trends are evident in the average individual thresholds as they were in the group thresholds. Masked threshold declines with increasing Δt at all ages. Both masked and unmasked thresholds decline progressively with age. The average individual thresholds of 3-month-olds and of adults are very similar to their respective group thresholds in all conditions. The average individual thresholds of 6-month-olds are consistently higher than group thresholds for that age. Average individual unmasked thresholds and masked thresholds for Δt from 10 to 200 ms were 5–10 dB higher than the corresponding group thresholds, but the average individual masked threshold at a Δt of 5 ms was nearly 20 dB higher than the corresponding group threshold among 6-month-olds. The difference appears to be due not to an artifact of the threshold calculation, but to between-infant differences in sensitivity. The difference between 3-month-olds' and adults' masked thresholds is greater than the difference between their unmasked thresholds, and the difference between their masked thresholds tends to increase with decreasing Δt. The threshold differences between 6-month-olds and adults is larger for a Δt of 5 ms than other conditions, but the difference is similar for Δt of 10–200 ms and the unmasked condition. Individual thresholds calculated from d' showed parallel results, with the exceptions that no thresholds could be calculated for 6-month-olds at Δt of 5 ms and that the thresholds of the 6-month-olds were somewhat closer to those of the 3-month-olds.

An analysis of variance (ANOVA) of threshold, with age and listening condition (four masking conditions and one unmasked condition) as factors, confirms these impressions. The age-by-listening condition interaction, the main effect of age, and the main effect of listening conditions were all highly significant (all p's<0.001). Within-age-group analyses of the effect of listening condition were used to explore the nature of the age by listening condition interaction. Among 3-month-olds, the effect of listening condition was significant ($p<0.001$), and all pairwise comparisons between listening conditions were significant (p's<0.001) except for the 10 vs 25 ms comparison ($p>0.05$). In other words, masked thresholds were higher than unmasked threshold for all Δt, and all but one increase in Δt lead to a significant decrease in threshold. Among 6-month-olds, the effect of listening condition was also significant ($p<0.001$). Masked threshold was significantly higher than unmasked threshold at all Δt. Masked thresholds at 200 and 25 ms and at 25 and 10 ms did not differ. Masked threshold at 5 ms was significantly higher than all other thresholds. Among adults, masked threshold at 200 ms was not different from unmasked threshold. All other masked thresholds were significantly higher than unmasked and the 200-ms masked threshold. While the 25- and the 5-ms masked thresholds were significantly different, the 10- and 25-ms and the 5- and 10-ms masked thresholds were not. Thus, introducing a forward masker at a Δt of 200 ms leads to an increase in threshold among infants, but not among adults. More significant increases in masked threshold are observed as Δt is decreased among 3-month-olds than among 6-month-olds or adults. This is consistent with a greater growth of forward masking with decreasing Δt among 3-month-olds than among older listeners.

C. Amount of masking

A more direct way to examine infants' relative susceptibility to forward masking would be to compare the amount of masking (masked minus unmasked threshold) produced by a forward masker across age groups. Amount of masking could not be calculated for the listeners tested here, because masked and unmasked thresholds were not obtained from the same listeners. However, an approximation to the amount of masking could be obtained by subtracting the average unmasked threshold for each age group from the average masked threshold of that age group.

The average amount of masking calculated from the group thresholds and from individual thresholds is plotted in Fig. 3. The estimates derived from group thresholds are within 5 dB of those derived from individual thresholds, with the exception of the 6-month-olds at 5 ms, for whom the individual threshold estimate indicates considerably more masking than does the group threshold estimate. Three-month-olds show more masking than either 6-month-olds or adults at all values of Δt by both estimates. On the other hand, 6-month-old and adult amounts of masking are very similar in all cases by the group threshold estimates and very similar at all Δt except 5 ms by the individual threshold estimates. The individual threshold estimate of 6-month-olds' amount of masking at Δt of 5 ms is higher than that estimate for adults.

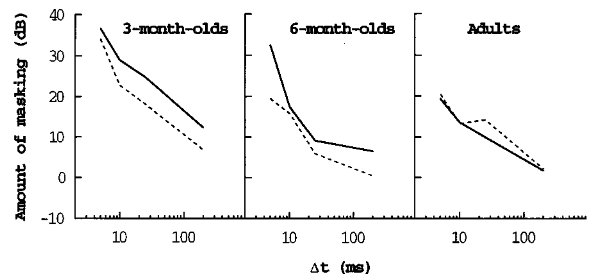

FIG. 3. Average amount of masking estimated by subtracting average unmasked threshold from average masked threshold at each Δt, for three age groups. The dashed lines indicate values calculated from thresholds estimated from the group psychometric functions. The solid lines indicate values calculated from average individual thresholds.

One can calculate ''amount of masking'' for each subject using the individual thresholds by subtracting the mean unmasked threshold for the appropriate age group from each masked threshold. An age X Δt ANOVA with pairwise *post hoc* comparisons of these values showed that 3-month-olds have significantly higher amounts of masking than adults and 6-month-olds at all values of Δt, while the 6-month-olds only have significantly higher amounts of masking than adults at Δt of 5 ms. The problem with this analysis is that the variance in the amount of masking estimated will simply equal the variance in masked threshold. The variance in ''real'' amounts of masking, calculated from masked and unmasked thresholds from the same individuals, would be expected to be higher than that of the masked (or unmasked) thresholds. Thus, a greater number of significant differences might be found for the estimates of amount of masking based on average unmasked threshold than for the individual amounts of masking. The significant differences between 3-month-olds and older listeners in estimated amounts of masking, then, may overstate the extent of the difference. However, following the same logic, one would still not expect 6-month-olds' individual amounts of masking to differ from those of adults.

III. DISCUSSION

The results of this experiment indicate that at least until 3 months of age, infants are more susceptible to forward masking than are adults, particularly at shorter values of Δt. Three-month-olds also appear to be susceptible to forward masking at longer masker–probe intervals than adults are. Susceptibility to forward masking appears to decline, however, between 3 and 6 months of age. By 6 months of age, it may be mature. All of these conclusions, of course, must be tempered by the limitations of the methods used to derive them. At the same time, the data obtained here are consistent with those in previous reports.

The forward-masking data obtained from the adult comparison group in this study are roughly comparable to those reported previously (e.g., Elliott, 1962a, 1962b; Jesteadt, Bacon, and Lehman, 1982). Probably the closest match in terms of stimulus conditions are the data of Elliott (1962b), who measured forward masking of a 10-ms, 1000-Hz probe by a

100-ms, broadband noise masker at 70 dB SPL, for Δt ranging from 0 to 50 ms. Elliott reported about 12 dB of masking at 5 ms, declining to about 4 dB at 25 ms. The adult listeners here were estimated to exhibit about 19 dB of masking at 5 ms, declining to about 8–10 dB at 25 ms. Thus, the current sample of adults exhibits somewhat more masking than Elliott's subjects, a result not surprising given their limited experience with the task.

Because a fixed masker level was used for all subjects and because infants' absolute thresholds are higher than those of adults, it is reasonable to consider how differences in sensation level may have contributed to the age differences observed in forward masking. Reducing the sensation level of the masker has two effects: a reduction in the amount of masking and a reduction in the slope of the function relating amount of masking to masker–probe interval (e.g., Jesteadt *et al.*, 1982). Thus, the amount of masking shown in Fig. 3 may underestimate infants' susceptibility to forward masking. Whether or not this is the case depends on the locus of the immaturity in absolute sensitivity relative to the locus of the immaturity in susceptibility to forward masking. For example, if the primary cause of the immaturity in absolute sensitivity is conductive, then the effective level of the forward masker would certainly be lower for the infants, and their relative susceptibility to forward masking would be greater than indicated by the amount of masking in Fig. 3. If immaturity in absolute sensitivity arises rostral to the site(s) which limit detection under forward masking, then the level of the forward masker would be effectively the same at all ages. Given that neither the mechanisms underlying forward masking nor the site of immaturities in absolute sensitivity have been established, it is impossible to draw a conclusion about this issue. However, assuming that the inner ear is mature, peripheral conductive immaturity would be expected to attenuate the sound in the region of 1000 Hz by about 3 dB for 3- or 6-month-olds (Keefe *et al.*, 1993). That difference in effective masker level would be expected to produce a very small difference in the amount of masking produced. Moreover, the fact that infants' function relating amount of masking to masker–probe interval is either steeper than or the same as that of adults argues against sensation level as a primary explanation for the observed age differences in forward masking.

The 3-month-olds' poor performance under forward-masking conditions is striking. There is a substantial difference between 3-month-olds and adults in threshold and in amount of forward masking, no matter which infant data one chooses for the comparison. Lasky's (1991) report is the only previous study of forward masking in human infants. Lasky reported that an 82-dB SPL broadband noise with Δt of 10 ms elevated click-evoked ABR thresholds of 1–3-day-old infants 6 dB more than it elevated adult thresholds. This is a considerably smaller age difference than the 10–20-dB difference observed psychophysically with a less intense masker and older infants. Thus, it is unlikely that immaturity at or peripheral to the auditory brainstem can account for much of the psychophysical age difference. It is still possible that immaturity of neural structures central to the brainstem is involved. Unfortunately, the existing literature on the development of evoked potentials originating in the auditory thalamus or cortex (e.g., Jerger *et al.*, 1987; Kraus *et al.*, 1985; Stapells *et al.*, 1988), while consistent with the idea that the infant's neural response is more susceptible to the effects of prior stimulation, does not permit direct comparison to either Lasky's or the present results. Jerger *et al.* (1987) reported that among 2–6-month-old infants, a slow positive peak in the middle latency response (MLR) was only observed when 500-Hz tone bursts were presented at rates less than 4/s. Adult MLRs are routinely recorded at rates greater than 10/s (e.g., Kraus *et al.*, 1985), but the difference in sensitivity to rate of stimulation is not readily converted to an age difference in amount of forward masking. In any case, mounting evidence that forward masking reflects retrocochlear processes in adults (Shannon, 1990; Turner *et al.*, 1994), and recent demonstrations of the relationship between evoked potential and perceptual development (Werner, Folsom, and Mancl, 1993, 1994) buttress the hypothesis that primary neural immaturities beyond the level of the brainstem may underlie immaturity in forward masking.

On the other hand, it seems clear that 6-month-old infants are less susceptible to forward masking than are 3-month-olds. In fact, 6-month-olds appear to be nearly mature in their susceptibility to forward masking, with the possible exception of forward masking at very short Δt. Given the high variability in 6-month-olds' performance at 5-ms Δt and the small number of 6-month-olds providing data, it is difficult to interpret the results in this condition. With reference to the evoked potential studies just cited, however, it should be noted that 6-month-olds may well show adultlike forward masking effects, although their auditory evoked potentials remain immature.

That infants exhibit more forward masking than adults is consistent with the hypothesis of Trehub *et al.* (1995) that infants are more susceptible to adaptation effects than adults are. Trehub *et al.* used this hypothesis to explain why infants appear to be so much more immature in gap detection when they are tested using continuous stimuli rather than very short duration tone pips. One aspect of the present results that is not consistent with that idea is the fact that while infant susceptibility to forward masking decreases between 3 and 6 months of age, infant gap-detection thresholds do not change over the same age period (Werner *et al.*, 1992).

As is always the case in the study of development, the possibility that immaturity of processes outside the primary auditory pathway influences infants' performance in a psychophysical test must be considered. Several authors have argued that age differences in thresholds of the order of magnitude reported here cannot in any case be accounted for by general inattention (e.g., Schneider and Trehub, 1992; Wightman and Allen, 1992; Viemeister and Schlauch, 1992). It is clear in any case that a general tendency to inattention cannot account for the greater susceptibility to forward masking seen in infants, for if infants were simply off-task a certain proportion of the time, we might expect that their unmasked and masked thresholds would be similarly affected (see also Bargones *et al.*, 1995). That infants took about as many trials to learn to respond to the probe in the presence of a forward masker as they did to the unmasked probe argues against the idea that infants tended to be more inattentive in the masking conditions. Moreover, it is not clear why inattentiveness would be greater for shorter Δt. Similarly, if the difference between 3- and 6-month-olds were due to methodological limitations, then those limitations would have to differentially affect masked over unmasked thresholds.

Werner and Bargones (1991) showed that the presence of a spectrally distant, simultaneous noise raised tone-detection thresholds among 6-month-old infants, but not among adults, by 5–10 dB. This type of masking is often referred to as informational masking. If infants are unable to ignore a temporally distant masker, just as they are unable to ignore a simultaneous masker that is spectrally distant from the probe, then they might appear to be especially susceptible to the effects of a forward masker. In other words, failure to limit listening to the expected time of occurrence of the probe would add noise to the decision process and increase masked threshold. Neff and her colleagues have clearly shown that adults' thresholds for a tone can be elevated by the simultaneous presentation of multiple, spectrally distant, random-frequency tones (Neff, 1995; Neff and Callaghan, 1988). Allen and Wightman (1995) have recently reported that thresholds are unmeasurable for most 3–4-year-olds when a single, spectrally distant, random-frequency tone is presented simultaneously with a probe, although the effect of the random-frequency tone is similar for adults and children from whom thresholds can be obtained. Werner and Bargones' result suggests that infants have difficulty ignoring a simultaneous masker, even when its frequency is certain. In the present context, it is interesting that adults can readily ignore multiple, spectrally distant, random-frequency forward maskers (Neff, 1991). It may be that 3-month-olds cannot ignore a forward masker in any condition. It appears that 6-month-olds can efficiently limit listening to the appropriate time, as they, like adults, exhibit little or no forward masking when the probe follows the masker by at least 200 ms.

It is difficult to choose between these hypotheses on the basis of the current data. For example, if adding a forward masker, at any Δt, raises infants' thresholds above unmasked by some amount, but the function relating Δt to masked threshold for infants simply parallels that of adults, then an informational masking account may be more tenable than a primary auditory system explanation. In the current data, unfortunately, the group threshold analysis seems to suggest a more dramatic decline in forward masking with increasing Δt among 3-month-olds, but not 6-month-olds, while the individual threshold analysis shows 6-month-olds, but not 3-month-olds, with more dramatic declines in forward masking relative to adults. We may not be able to obtain sufficient psychophysical data from infants to discern such details. However, it may be possible to use other measures, such as evoked potentials, to try to determine the source of early immaturities in forward masking.

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[1]In any case, were frequency resolution to be poorer among infants or children than among adults, better temporal resolution would be predicted for young listeners.

[2]Psychometric functions including only complete data sets were compared to those including all test data to examine the possibility that incomplete data sets biased the group threshold estimates. For 3-month-olds, there was essentially no effect of including incomplete data sets. For 6-month-olds, group thresholds were 2–4 dB lower in three forward-masked conditions ($\Delta t=5$, 10, and 200 ms) when the incomplete data sets were excluded, but those in the other two conditions were not affected. Thus, the inclusion of incomplete data sets appeared to have little impact on group threshold estimates.

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