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Children's detection of pure-tone signals: Informational masking with contralateral maskers

Frederic L. Wightman^a, Michael R. Callahan, Robert A. Lutfi^b, Doris J. Kistler, and Eunmi Oh^c

Waisman Center, University of Wisconsin, Madison, Wisconsin 53705

Abstract

When normal-hearing adults and children are required to detect a 1000-Hz tone in a random-frequency multitone masker, masking is often observed in excess of that predicted by traditional auditory filter models. The excess masking is called informational masking. Though individual differences in the effect are large, the amount of informational masking is typically much greater in young children than in adults [Oh *et al.*, *J. Acoust. Soc. Am.* **109**, 2888–2895 (2001)]. One factor that reduces informational masking in adults is spatial separation of the target tone and masker. The present study was undertaken to determine whether or not a similar effect of spatial separation is observed in children. An extreme case of spatial separation was used in which the target tone was presented to one ear and the random multitone masker to the other ear. This condition resulted in nearly complete elimination of masking in adults. In young children, however, presenting the masker to the nontarget ear typically produced only a slight decrease in overall masking and no change in informational masking. The results for children are interpreted in terms of a model that gives equal weight to the auditory filter outputs from each ear.

I. INTRODUCTION

The research reported here addresses the general question of how children segregate and attend to target sounds in noisy backgrounds such as classrooms. A previous article (Oh *et al.*, 2001) described an experiment in which preschool children and adults were asked to detect a 1000-Hz sinusoid that was masked by a random multitone complex. The adult results confirmed many earlier reports (e.g., Lutfi, 1993; Neff and Green, 1987; Oh and Lutfi, 1998; Spiegel *et al.*, 1981) that random frequency multitone maskers produced considerably more masking than predicted by traditional auditory filter models. This excess masking, thought to be a central effect produced mainly by the uncertainty of the masker, has been called “informational masking” to distinguish it from the “energetic masking” predicted by filter models of the auditory periphery. As earlier studies showed (e.g., Neff and Dethlefs, 1995; Oh and Lutfi, 1998), informational masking varied non-monotonically with the number of masker components and was as great as 60 dB in some adult listeners. The data from the children produced a similar pattern, but with considerably greater amounts of informational masking. Individual differences were large, as in most previous studies (e.g., Neff and Dethlefs, 1995).

Simple modifications of the traditional auditory filter model that presume broader auditory filters in children (e.g., Allen *et al.*, 1989) fail to account for either the magnitude of the informational masking effect or its non-monotonicity with number of masker components. In contrast, the component-relative-entropy model (CoRE) proposed by Lutfi (1993) provides good fits to the data from both children and adults in the Oh *et al.* (2001) study. The CoRE model proposes that masking is determined by the variance of the outputs (in dB) of a number of peripheral auditory filters, not just the filter centered at the target frequency. The number of filters monitored (n) and the range of their center frequencies (W) are the two free parameters of the model. Thus, informational masking is the result of the inability of the listener to ignore all filter outputs except the one centered at the target frequency. According to the CoRE model, the adult-child differences are a result of the tendency of children to integrate information over a larger number of auditory filters than adults and not simply a result of wider auditory filters in children.

Efforts to understand the mechanisms and processes underlying the informational masking effects have led some researchers to explore stimulus manipulations that might reduce the size of the effect. Kidd *et al.* (1994, 1998) and Neff (1995), for example, suggested that informational masking in adults may result from an inability to segregate signal and masker perceptually. Kidd *et al.* (1994) reduced adult informational masking by as much as 40 dB by altering the stimulus presentation scheme, making the masker less “signal-like,” in order to enhance signal-masker segregation. Neff (1995) reported similar results, noting in addition the large individual differences in the extent to which the stimulus manipulations were successful in reducing informational masking. Some of the successful alterations reported in both the Kidd *et al.* (1994) and Neff (1995) studies amounted to attempts to separate the signal and masker spatially. One was achieved by presenting the masker to both ears and the signal to one ear (Kidd *et al.*, 1994), presumably producing a percept in which the masker was lateralized in the middle of the head and the signal at one ear. Others involved presenting the masker in phase to both ears with the signal phase inverted at one ear (masker probably perceived in the middle of the head and signal at the two ears) or presenting signal and masker to different ears (Neff, 1995). Kidd explored the spatial separation manipulation more directly in a later study (Kidd *et al.*, 1998) in which signals and maskers were presented from loudspeakers in an acoustically treated room. Spatial separation reduced informational masking by as much as 20 dB in this latter study. However, the results of at least one previous study would argue that the informational masking effects observed in children might be resistant to manipulations that would normally reduce or eliminate informational masking in adults. In a study of masking in infants, Werner and Bargones (1991) measured the detection threshold for a 1-kHz tone in quiet and in the presence of a 4–10-kHz noise band. A noise band two octaves above the signal frequency would not be expected to create any masking in adult listeners. In the infants, however, the noise raised detection threshold by about 10 dB. The effect could not be attributed to wider auditory filters in the infants, since increasing the level of the noise band by 10 dB caused only a 1–2-dB change in threshold. A pure tone and a high-frequency noise band are perceptually quite distinct, so one would expect the two stimuli to be readily segregated. However, for the infants in this study, a strong distraction or informational masking effect was evident. This suggests that those stimulus manipulations that reduce informational masking in adults may be less effective in children.

It is important to understand the impact on informational masking of spatial separation of target and masker if one is to relate informational masking data to a child's task of segregating and attending to auditory targets in a noisy classroom. In a typical classroom distracting sounds are spatially distributed and the target sound (the teacher's voice) usually originates from a fixed location. The signals, maskers, and listening environments used in most studies of informational masking have little in common with the classroom situation. Thus, this study was motivated, as others have been, by the desire to approximate classroom listening conditions

more closely. Here we study the impact of a simple kind of “spatial” separation of target and masker on informational masking in children. We achieve spatial separation, as did Neff (1995) in the “cross-ear” condition of her study of adult listeners, by presenting the target signal to one ear and the multitone masker to the other. Our rationale for this approach is twofold. First, it is easy to implement, and since the task remains essentially the same, no additional training of the children is required. Second, the CoRE model can easily be modified to predict the results by adding a second set of auditory filters to be monitored and a weighting parameter for the nontarget ear. To minimize “central masking,” the known cross-ear masking effect that is presumably unrelated to informational masking (Wegel and Lane, 1924; Zwislowski *et al.*, 1968; Mills *et al.*, 1996), we present low-level (60 dB SPL) maskers that consist of frequencies remote from that of the signal.

II. METHODS

A. Listeners

Seven preschool children participated in this study. Five of the seven had been tested in the earlier study of informational masking in children (Oh *et al.*, 2001) and two had participated in the earlier study of individual differences (Lutfi *et al.*, 2003). All the preschool children were selected from the Waisman Center Early Childhood Program on the basis of their parents’ consent and their own willingness to participate. At the time of testing their ages ranged from 4.2 to 5.6 years. All eight of the previously tested adults (UW—Madison students) also participated in this study. In addition, 28 school-aged children participated. These children, aged 6.7–16.2 years, had been recruited from families of Waisman Center employees into the study of individual differences (Lutfi *et al.*, 2003) in which the identical stimulus conditions as in Oh *et al.* (2001) were presented. The adults and school-aged children were paid for their participation, and the preschoolers were rewarded at the end of each session with small toys.

All listeners demonstrated normal hearing, as indicated by pure-tone thresholds less than 15 dB HL (ANSI, 1989) at octave frequencies from 250 to 4000 Hz. Because middle ear problems are common in young children, tympanometry was performed on each child (preschoolers only) prior to each session using a screening tympanometer (GSI-27A Auto-Tymp) calibrated to ANSI specifications (ANSI, 1987). The child was allowed to continue only if peak-compensated static admittance was normal. Other listeners were not tested on days when they reported having a cold or other upper-respiratory problem.

B. Stimuli

As in the previous study (Oh *et al.*, 2001), the signal was a 1000-Hz tone burst, presented simultaneously with a multitone masker that was derived from a sample of Gaussian, bandpass filtered (0.1 to 10 kHz) noise. A given masker was generated by selecting one noise sample (randomly with equal probability) from a pool of 100 and computing its discrete magnitude and phase spectrum. Then, depending on the condition being tested, a specific number of its frequency components was selected randomly, and those components were summed, using the original magnitudes and phases. The number of masker components (2, 10, 20, 40, 200, 400, or 906) was varied across different experimental conditions but was fixed within an experimental session. A “broadband” condition was included in which the actual selected noise burst was presented as a masker (roughly equivalent to 3700 components). In all conditions masker components within a 160-Hz band arithmetically centered at 1000 Hz were excluded. A “quiet” condition was also included, with no masker presented, to estimate absolute threshold for the 1000-Hz signal.

Both signal and masker were gated on and off together with 10-ms, $\cos^2$ onset/offset ramps for a total duration of 370 ms. The rms level of the masker was 60 dB SPL in all conditions.

In the broadband condition the spectrum level of the noise was approximately 20 dB SPL. The dB levels of the individual masker components were random, approximately normally distributed (component amplitudes were Rayleigh distributed) with a standard deviation of 5.6 dB. Since the overall level of the masker was constant, the average levels of the individual components would vary inversely with the number of components. The maximum level of the signal was limited to 84 dB SPL. The signal and the masker were computer generated and played over a 16 bit digital-to-analog converter (Tucker-Davis Technologies DD1) at a sampling rate of 44.1 kHz. All stimuli were presented monaurally, the signal to the listener's left ear and the masker to the right ear, through Sennheiser model HD-414 headphones. The sound levels produced by the Sennheiser headphones were estimated with a loudness balancing procedure using calibrated TDH-49 headphones and adult listeners.

C. Procedure

A staircase, cued two-interval, forced-choice (2AFC) procedure was used to estimate signal threshold. Each trial was preceded by a cue, which consisted of the presentation of a bird picture on a computer screen and a simultaneous unmasked stimulus tone at 60 dB SPL. The child was told that the tone was a "bird sound." Note that the "bird sound" was always presented monaurally to the left ear. Two successive stimulus intervals were then presented with a 700-ms silent interval between them. Each stimulus interval was marked (on the computer screen) by a flashing square with the numeral "1" or "2" on it. One of the two intervals contained a masker sample and the other contained a different masker sample with the signal added to it. The signal occurred in the first or second interval with equal probability. The listener's task was to select the interval that contained the signal. The instructions were "Listen to the two sounds presented with the two boxes and point to the box that has the bird sound." Correct responses were reinforced by presenting a few pieces of a picture puzzle. The listener was allowed to choose pictures for the puzzle (cartoon characters, animals, his/her own pictures, etc). The goal was to complete the puzzle within a block of trials.

The starting signal level was selected so as to make the signal clearly audible to the listener. On each of the next four trials the signal level was decreased in 8-dB steps and then was increased in 8-dB steps back to the starting level. This up-down pattern was continued for a total of 40 trials, producing five trials at the highest and lowest levels and ten trials at each of the three intermediate levels. The signal level was varied by a programmable attenuator (Tucker Davis Technologies PA4). At least three blocks of trials were completed for an experimental condition. If performance levels near 100% and 50% (chance) were not obtained for the highest and lowest signal levels, an additional block of trials was obtained (in some, but not all cases) with the starting level adjusted either up or down so that desirable performance levels were observed at both extremes.

Each listener was tested in a double-walled, sound-attenuating chamber. Two experimenters accompanied a child listener. One experimenter set up an appropriate starting level, initiated stimulus presentation when the child was ready for the next trial, and entered a "1" or "2" when the child made a response by touching one of the boxes on the screen or by calling out the number. The other experimenter was present to satisfy security regulations. The experimenters interacted with the child in an attempt to hold his/her interest during the session and to remind the child that the target sound was the monaural "bird sound."

Practice trials were given until the listener appeared familiar with the task. The children completed three or fewer blocks of 40 trials each day, depending on their willingness to continue and time availability. It took the preschool children 8–10 min to complete a block of trials and they participated for no longer than 30 min on any single day. School-aged children and adults were tested in the same conditions as the preschool children and required approximately 5 min to complete each block of 40 trials. The school-aged children participated

for a minimum of an hour on each day, and the adult listeners (and some of the older school-aged children) participated for 2 h on each day. All listeners first completed the condition in which the signal was presented alone (“quiet” condition), and then the condition involving the broadband noise masker. Next they completed the experimental conditions in which the signal was presented with the multitone maskers. These latter experimental conditions were presented in random order. Finally, all the listeners in the current study were tested after they had participated in a similar study of informational masking in which identical signal and masker stimuli had been presented. In those previous studies signal and masker had been presented to the same ear (Oh *et al.*, 2001; Lutfi *et al.*, 2003).

D. Data analysis

A three-parameter logistic function was fit to the data relating percentage of correct responses to signal level for each listener in each condition using a maximum likelihood criterion. The three parameters of the logistic were used to derive the slope, the signal level at which the function crossed 75% correct, and the upper asymptote. This third parameter allowed estimation of the extent to which performance (especially for the children) would not reach 100% correct at the highest signal levels. The fitting procedure was implemented exactly as described by Wichmann and Hill (2001a, b). In addition to providing estimates of the three parameters of the fitted function, the procedure included a “bootstrapping” or simulation phase that provides estimates of confidence limits on all three parameters. The simulation phase estimated the sampling distributions of the three logistic parameters. Using the values of percent correct at each signal level from the fitted function as means, and assuming binomially distributed percent correct values, a simulated percent correct at each signal level was randomly drawn and a logistic was fit to these values. This was repeated 10 000 times to provide 10 000 estimates of each of the three logistic parameters. The 2.5% and 97.5% points from these sampling distributions were then taken as the 95% confidence limits. The sampling distribution of the threshold parameter (signal level at 75% correct) was asymmetric in many cases, thus producing asymmetric confidence intervals in these cases. Since the amount of data obtained from children was quite limited, and since individual differences were large, we viewed the estimation of confidence limits on psychometric function parameters from each listener in each condition as a critical component of the data analysis procedures. The Wichmann and Hill (2001b) procedure is the first of which we are aware that offers confidence limit estimates that are not dependent on asymptotic normality assumptions.

III. RESULTS

All of the listeners in this study had also participated in earlier studies (Oh *et al.*, 2001; Lutfi *et al.*, 2003) that used identical procedures and nearly identical stimulus conditions. In the previous experiments the target signal and the maskers were presented to the same ear (ipsilateral masker), and in the current study the signal is presented to one ear and the masker is presented to the other (contralateral masker). Since the main purpose of the experiment reported here is a comparison of results from the ipsilateral and contralateral conditions, the data from the previous articles are reproduced here (after reanalysis according to the procedures described above) for the reader’s convenience.

Figure 1 shows the data from the adult listeners. Listener ages are given at the top of each panel. In this figure, total masking is defined as the dB difference between signal threshold in quiet and threshold in the presence of a masker. Each data point (and associated 95% confidence interval) represents total masking for a fixed number of masker components. Filled symbols are data from the ipsilateral masker condition (previously reported in Oh *et al.*, 2001, and reanalyzed for presentation here), and open symbols are data from the contralateral masker condition. The horizontal dashed lines in each panel show the listener’s threshold for the signal

with a broadband noise masker (solid: ipsilateral; dashed: contralateral). Informational masking is revealed by thresholds higher than those predicted on the basis of a simple filter model. Since no masker included energy within a 160-Hz rectangular band centered at the target frequency, most of the masking, especially for small numbers of masker components, is thought to be informational. A very conservative view is that any threshold higher than that obtained with broadband noise reflects the contribution of informational masking (Oh and Lutfi, 1998). Here, that means that any threshold above the horizontal dashed lines includes a significant informational masking component. Of course, even the masking produced by broadband noise may contain some informational masking, as has been argued by Lutfi (1990), but the extent to which thresholds exceed the broadband noise threshold would be expected to reflect additional informational masking. Note that using this criterion only three of the eight adults in this study show significant amounts of informational masking and only in the ipsilateral condition. Large individual differences in amounts of ipsilateral informational masking are typical of past work (e.g., Neff and Dethlefs, 1995), and when the current results are considered in a broader context they should not be considered unusual. For example, Lutfi *et al.* (2003) collected complete ipsilateral masking functions from 84 listeners, including nearly 50 adults, 8 of whom also participated in the current study. Those 8 adults did not represent the extremes of the larger group.

For the adults, the most dramatic results is the fact that there is little if any masking in the contralateral condition (signal and maskers in opposite ears). Thus, putting the masker in the opposite ear not only eliminated informational masking for the adults, but it eliminated nearly all masking. This result is consistent with previous studies of central masking (e.g., Mills *et al.*, 1996), all of which show that central masking is a very small effect when maskers do not overlap spectrally with the signal and are presented at moderate levels. It is also consistent with the results from the contralateral-masking condition in the informational masking study reported by Neff (1995).

Figure 2 shows the data obtained from the preschoolers, plotted as in Fig. 1. Note that the preschoolers [ipsilateral data previously shown in Oh *et al.* (2001) and reanalyzed for presentation here] show large amounts of informational masking in the ipsilateral condition (solid symbols above the solid horizontal line) and large individual differences. More importantly for the purpose of the present study, note that the impact of presenting signal and masker contralaterally is not to eliminate masking, as occurs in adults, but simply to reduce it by an average of 20 dB. In other words, although masking is reduced overall in the contralateral condition, the same masking pattern (masking as a function of the number of masker components) is observed in the contralateral condition as in the ipsilateral condition; informational masking, defined here as the dB difference between masking in a given condition and masking in the broadband condition, is not reduced at all. The large individual differences that are apparent in the data shown in Fig. 2 are particularly striking when one considers the differences between the ipsilateral and contralateral results. For example, listener STJ's threshold with a broadband noise masker is lowered only about 10 dB by placing the masker in the opposite ear, and this contralateral threshold is still more than 20 dB above quiet threshold for this listener. In contrast, listener SVU's contralateral broadband threshold, which is 30 dB lower than the comparable ipsilateral threshold, is very near quiet threshold. In both listeners, however, large amounts of informational masking are evident in both ipsilateral and contralateral conditions. The fact that masking persists with a contralateral broadband masker is difficult to explain if one assumes that the masking produced by broadband noise is energetic, i.e., predictable by a simple auditory filter model.

Figures 3(a) and (b) show the results obtained from the 28 school-aged children. The individual masking functions have been divided into two groups according listener age. The "younger school-age" group includes listeners aged 6.7–10.4 years and the "older school-age" group

includes those aged 10.5–16.4 years. Visual inspection of the ipsilateral data in the two groups [previously reported in Lutfi *et al.* (2003), and reanalyzed for presentation here] reveals few obvious group differences and large individual differences in each group. In both groups there are listeners with large amounts of informational masking in both the ipsilateral and contralateral conditions. There are several listeners in the younger school-age group (e.g., SVP, SUV, SUX) who produced adultlike masking functions, with little or no masking in the contralateral condition and modest informational masking in the ipsilateral condition. There are also several listeners in the older school-age group (e.g., SVF, SVN, SVK) who produced masking functions similar to those from the preschoolers, with large amounts of informational masking in both ipsilateral and contralateral conditions.

The large individual differences in the amounts of masking and in the shapes of the masking functions would lead one to be very cautious with summary data. Nevertheless, plots of the mean amounts of total masking in the two conditions for each of the four listener groups reveals some interesting trends. Figure 4 shows the mean masking functions, with 95% confidence intervals plotted around each mean to allow visual interpretation of the statistical significance of differences.

Note first that the mean amounts of masking with a broadband noise masker are roughly the same in all four groups, in both the ipsilateral and contralateral conditions. In the ipsilateral condition the mean amount of masking with a broadband noise masker is about 35 dB, for the preschoolers, the younger and older school-age children, and for the adults. In the contralateral condition, the mean amount of masking with the broadband masker is only about 6 dB, consistent with previous results from studies of central masking. These are important results since they suggest that in this one condition, with a more or less nonvarying broadband masker, children and adults are performing the task at about the same level of proficiency. Thus, the data from the broadband conditions reveal little evidence of adult–child differences in auditory function.

In contrast, a clear age effect is evident in the mean masking functions from both the ipsilateral and contralateral conditions. In the ipsilateral conditions the age effect is manifest by decreases with increasing age of both the amount of masking with small numbers of masker components and the maximum amount of informational masking (masking above the solid horizontal line). The same is true of the masking functions from the contralateral conditions, although in this case there is an especially dramatic decrease in both amount of masking and maximum informational masking between the preschool and younger school-age group.

The psychometric function fitting procedures used in this study provided estimates of threshold, slope, and upper asymptote. Thus far we have discussed only the threshold estimates. The slopes of the psychometric functions, which are indicative of the variance of the decision variable, varied considerably across both conditions and age groups. The CoRE model makes specific predictions about how the slope parameter should vary with these two variables. A full explanation of how those predictions are generated and the extent to which they are consistent with the data described here will be the subject of a forthcoming article.

The upper asymptote parameter of the fitted psychometric functions estimates the extent to which performance on each individual run would fail to reach 100% correct at the highest signal levels. In the past we and others have argued that an upper asymptote less than 100% might indicate that on a certain fraction of trials the child is inattentive, and thus simply “guessing” (e.g., Wightman and Allen, 1992; Lutfi and Wightman, 1996). In the current study, however, guessing is not the only response strategy that would lower the upper asymptote. Attending only to the nontarget auditory filters on a fraction of the trials would have the same impact on the psychometric function as guessing (Lutfi and Wightman, 1996), and it is

impossible from threshold estimates alone to tease apart the two strategies. The estimated upper asymptotes were less than 95% (never less than 80%) on 24% of the runs obtained from the preschool children, 11% of the runs from younger school-aged children, 12% of the runs from older school-aged children, and 6% of the runs from adults.

IV. DISCUSSION

This experiment was motivated by the possibility that the large amounts of informational masking previously observed in young children would be reduced if the target and the maskers were spatially separated, as in most everyday listening situations. Previous research with adult listeners (Kidd *et al.*, 1994, 1998) suggested that large reductions in informational masking could be obtained by spatial separation. If the same were true with children, concerns about large informational masking effects in classroom environments could be somewhat alleviated.

In an attempt to simplify the stimulus generation procedures and to allow more complete interpretation of the results by application of the CoRE model, we chose to study an extreme kind of “spatial” separation, namely contralateral presentation of target and maskers. This stimulus configuration, and the percepts that it produces, are not representative of everyday listening, but we feel that it is a reasonable starting point. Our working hypothesis, yet to be tested, is that the reduction in informational masking listeners achieve with contralateral presentation would probably represent an upper bound on the reduction they would achieve in more realistic listening conditions.

For the adult listeners in our study, contralateral presentation of target and masker eliminated not only informational masking but nearly all masking. This result was not entirely unexpected, given the history of work on central masking. For the preschool children, contralateral presentation produced almost no reduction in informational masking, although total masking was reduced by about 20 dB on average. Some of the preschool children produced large amounts of masking in the contralateral broadband condition as well, which might indicate that some masking by broadband noise is informational (Lutfi, 1990). The school-aged listeners produced results that spanned the entire range between the adult and preschool results.

It is possible that aspects of training and prior experience may have contributed to the large individual differences, especially in the data from the children. Although training can exert a significant impact on adult performance (Watson, 1980; Leek and Watson, 1984; Watson and Foyle, 1985), improvements are observed only after extensive training over long time periods. Moreover, the adults in this study performed optimally in the contralateral conditions, and the performance of the children when the masker was broadband noise was almost the same as that of adults in both ipsilateral and contralateral conditions. Whether or not the children might have benefitted from more training with fewer numbers of masker components is not known, but in this context it should be mentioned that one listener in the cross-ear condition of the Neff (1995) study apparently required eight to ten runs to achieve asymptotic performance, so training in conditions such as ours may be an important issue. It is also possible that children may have required more elaborate instructions (emphasizing the fact that the target was only in the left ear), or may have achieved better performance given a different order of conditions (e.g., contralateral first). These are important questions, the answers to which must await further research. However, with regard to the instructions issue, there is every reason to think that the children were fully aware that the target was monaural and in the left ear. An unmasked target was presented on each trial as a cue, and the paradigm insured that a high S/N ratio target would be presented periodically throughout the run. With regard to the condition order issue, nothing can be said, since for all listeners, the ipsilateral conditions were tested before the contralateral conditions. Adults obviously adjusted their listening strategy to focus on the target ear in the contralateral conditions, and children did not. The practice trials and the unmasked cue

presentations were included to encourage children to adjust their listening strategy appropriately, but the effectiveness of these procedures is unknown.

The component-relative-entropy (CoRE) model proposed by Lutfi (1993) offers a context in which the current results can be understood. According to this model, listeners are assumed to detect a target signal by implementing a decision rule based on the level outputs of n auditory filters. An ideal observer would monitor the output of only one auditory filter, the one centered on the target frequency. The inability to ignore masker tones, which produces the informational masking effect, is represented by monitoring additional auditory filters, the outputs of which are independent of target presence or absence. Most of the variance (82%) in the masking functions for all age groups in the ipsilateral condition can be accounted for by the value of n (Lutfi *et al.*, 2003). A similar approach can be used to explain masking in the contralateral condition without adding additional parameters to the model. To the extent that listeners can focus attention on the target ear, placing the masker in the opposite ear could be expected to reduce n , the number of attended auditory filters. A change in n has the effect of scaling the predicted masking function, leaving the threshold with a broadband masker unchanged. Thus, the model makes a simple prediction about the relationship between the ipsilateral and contralateral masking functions: the contralateral function should be a scaled version of the ipsilateral function. The best fitting scale factor would indicate the extent to which n was reduced by placing the masker in the opposite ear. In fact, the square root of the scale factor is equal to the proportion by which n is reduced. Scale factors greater than 1.0 would suggest that n was actually larger in the contralateral condition. The dot-dashed lines in Fig. 4 show the predictions of the model applied to the group mean contralateral data. The best fitting scale factor (shown in the figure for each group) is slightly greater than 1 for the preschoolers and close to 0 for the adults. In other words, the model predicts that the impact of placing the masker in the contralateral ear is actually to increase the number of monitored auditory filters for preschoolers and effectively to reduce to 1 the number of monitored filters for adults. Increasing the width of the auditory filters in the model cannot account for either the ipsilateral or the contralateral results.

The concept of selective attention is implicit in the CoRE model. The basic assumption of the model, that decisions are based on the outputs of “monitored” auditory filters, requires an attentional mechanism to guide the monitoring. Thus, informational masking, which can be characterized as an inability to ignore irrelevant auditory information, might be viewed as a failure of selective attention. Given the considerable literature on selective attention in children, it may be revealing to consider the current informational masking results in the context of psychological research on attention and the development of attention.

The early years of a child’s life are marked by several developmental transitions in attention that have been revealed primarily by studies of the child’s pattern of looking at the world. These transitions, most of which occur before age 4–5, reflect the development of a two-stage attentional system (Neisser, 1967; Ruff and Rothbart, 1996). The first stage is characterized by orienting and investigating, and the second by higher level control. There is both behavioral and physiological evidence supporting the development of these two “anatomically and functionally separate” stages of selective attention (Ruff and Rothbart, 1996, Chap. 3).

It is the role of the first stage (orienting, or preattentive) to discriminate among task-relevant and task-irrelevant stimuli (Hagen and Hale, 1973). The second stage (higher level control, or focal) controls what is selected for further processing. The high levels of informational masking observed in children could reflect immaturity of either the first or second stage. Evidence from a series of “central-incidental learning” studies leads us to speculate that it may be the second stage that is the source of informational masking.

In an auditory version of the central-incident learning paradigm (Doyle, 1973), children were asked to repeat target words spoken by a male and presented simultaneously with distracter words spoken by a female. The number of target words correctly repeated was the main performance measure. Retention of both the target and the distracter words was also measured. The main results were that the distracter impaired the word-repeating performance of the younger children (age 8 years) more than that of the older children (age 14), that retention of the target words increased with age, and that retention of the distracter words remained constant across the age groups. Because retention of the distracter words remained constant, the results were interpreted to suggest that the better performance of older children was "...due not to a greater ability to filter out distracting material at an earlier stage of processing, but in large part to an ability to inhibit intrusions from the distracting material..." Along similar lines, Humphrey (1982) reported a dramatic decrease in the impact of distracters on performance in visual recognition and recall tasks between age 4 and age 11, reflecting, perhaps, maturation of the second stage of the selective attention system. Although most of the research on the development of selective attention has focused on the visual modality, an important study by Conroy and Weener (1976), using the central-incident learning paradigm, provided results that argued for parallel developmental trajectories for visual and auditory selective attention. Although the connection between informational masking and selective attention may be speculative, the fact that the processes underlying both seem to develop well into the school years is suggestive. The decrease in distraction effects between ages 4 and 11 reported by Humphrey (1982) in a visual task may reflect maturation of the same processes that modulate informational masking, which also decreases dramatically in that same age range (cf. data from Preschool and Younger School Aged groups in Fig. 4).

The research reported in this paper examined the impact of spatial separation of targets and distracters with the aim of contributing to our understanding of the process of stimulus segregation in noisy backgrounds such as classrooms. The previous research on selective attention in preschool and school-aged children is clearly relevant to the stimulus segregation issue. Nearly all of this research suggests that selective attention is not at adult levels until early adolescence, or even later. The results reported here are consistent with the previous selective attention results. Although the generalizability of the current contralateral target and masker configuration to everyday listening situations is tenuous, the previous selective attention results, combined with the results reported here, do not lead to optimistic predictions about the ability of young children to reduce the masking effect of uncertain maskers by spatial separation. Nevertheless, the prediction of little or no reduction in masking effectiveness with spatial separation should be tested in more natural listening environments which afford all the usual cues to spatial position (interaural differences, etc.). In addition, the potential advantage for children of other sound source segregation techniques should be studied. For example, Kidd *et al.* (1994) showed that stimulus configurations that made the maskers less "signal-like" presumably allowed listeners to segregate target from maskers and thus led to reductions in informational masking for his adult listeners. It is entirely possible that although children do not seem to be able to take advantage of spatial cues to segregate target and maskers, they may be able to use some of these other segregation cues (cf. Werner and Bargones, 1991).

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References

- Allen P, Wightman F, Kistler D, Dolan T. Frequency resolution in children. *J. Speech Hear. Res* 1989;32:317–322. [PubMed: 2739383]

- ANSI. ANSI S3.9–1987, American National Standards specification for instruments to measure aural acoustic impedance and admittance (aural acoustic immittance). New York: American National Standards Institute; 1987.
- ANSI. ANSI S3.9–1989, American National Standards specification for audiometers. New York: American National Standards Institute; 1989.
- Conroy RL, Weener P. The development of visual and auditory selective attention using the central-incident paradigm. *J. Exp. Child Psychol* 1976;22:400–407. [PubMed: 993722]
- Doyle A. Listening to distraction: a developmental study of selective attention. *J. Exp. Child Psychol* 1973;15:100–115. [PubMed: 4706960]
- Hagen, JW.; Hale, GH. The development of attention in children. In: Pick, AD., editor. *Minnesota Symposia on Child Psychology*. Minneapolis: Univ. of Minnesota; 1973. p. 117–140.
- Humphrey MM. Children's avoidance of environmental, simple task internal, and complex task internal distractors. *Child Dev* 1982;53:736–745.
- Kidd G Jr, Mason CR, Rohtla TL, Deliwala PS. Release from masking due to spatial separation of sources in the identification of nonspeech auditory patterns. *J. Acoust. Soc. Am* 1998;104:422–431. [PubMed: 9670534]
- Kidd G Jr, Mason CR, Deliwala PS, Woods WS, Colburn HS. Reducing informational masking by sound segregation. *J. Acoust. Soc. Am* 1994;95:3475–3480. [PubMed: 8046139]
- Leek MR, Watson CS. Learning to detect auditory pattern components. *J. Acoust. Soc. Am* 1984;76:1037–1044. [PubMed: 6501698]
- Lutfi RA. How much masking is informational masking? *J. Acoust. Soc. Am* 1990;88:2607–2610. [PubMed: 2283433]
- Lutfi RA. A model of auditory pattern analysis based on component-relative-entropy. *J. Acoust. Soc. Am* 1993;94:748–758. [PubMed: 8370881]
- Lutfi RA, Wightman FL. Guessing or confusion? Analytic predictions for two models of target-distracter interference in children. *Abst. Assoc. Res. Otolaryngol* 1996;19:142.
- Lutfi RA, Kistler DJ, Oh EL, Wightman FL, Callahan MR. One factor underlies age-related differences in auditory informational masking. *Percept. Psychophys* 2003;65(3):396–406. [PubMed: 12785070]
- Mills JH, Dubno JR, He N. Masking by ipsilateral and contralateral maskers. *J. Acoust. Soc. Am* 1996;100:3336–3344. [PubMed: 8914315]
- Neff DL. Signal properties that reduce masking by simultaneous, random-frequency maskers. *J. Acoust. Soc. Am* 1995;98:1909–1920. [PubMed: 7593915]
- Neff DL, Dethlefs TM. Individual differences in simultaneous masking with random-frequency, multicomponent maskers. *J. Acoust. Soc. Am* 1995;98:125–134. [PubMed: 7608391]
- Neff DL, Green DM. Masking produced by spectral uncertainty with multicomponent maskers. *Percept. Psychophys* 1987;41:409–415. [PubMed: 3601622]
- Neisser, U. *Cognitive Psychology*. New York: Appleton; 1967.
- Oh EL, Lutfi RA. Nonmonotonicity of informational masking. *J. Acoust. Soc. Am* 1998;104:3489–3499. [PubMed: 9857508]
- Oh EL, Wightman FL, Lutfi RA. Children's detection of pure-tone signals with random multitone maskers. *J. Acoust. Soc. Am* 2001;109:2888–2895. [PubMed: 11425131]
- Ruff, HA.; Rothbart, MK. *Attention in Early Development*. New York: Oxford U.P.; 1996.
- Spiegel MF, Picardi MC, Green DM. Signal and masker uncertainty in intensity discrimination. *J. Acoust. Soc. Am* 1981;70:1015–1019. [PubMed: 7288038]
- Watson CS. Time course of auditory perceptual learning. *Ann. Otol. Rhinol. Laryngol. Suppl* 1980;74:96–102. [PubMed: 6786201]
- Watson CS, Foyle DC. Central factors in the discrimination and identification of complex sounds. *J. Acoust. Soc. Am* 1985;78:375–380. [PubMed: 4031244]
- Wegel RL, Lane CE. The auditory masking of one pure tone by another and its probable relation to the dynamics of the inner ear. *Phys. Rev* 1924;23:266–285.
- Werner L, Bargones J. Source of auditory masking in infants: distraction effects. *Percept. Psychophys* 1991;50:405–412. [PubMed: 1788029]

- Wichmann FA, Hill NJ. The psychometric function: I. Fitting, sampling, and goodness of fit. *Percept. Psychophys* 2001a;63:1293–1313. [PubMed: 11800458]
- Wichmann FA, Hill NJ. The psychometric function: II. Bootstrap-based confidence intervals and sampling. *Percept. Psychophys* 2001b;63:1314–1329. [PubMed: 11800459]
- Wightman, F.; Allen, P. Individual differences in auditory capability among preschool children. In: Werner, LA.; Rubel, EW., editors. *Developmental Psychoacoustics*. Washington, DC: American Psychological Association; 1992. p. 113-133.
- Zwislocki JJ, Buining E, Glantz J. Frequency distribution of central masking. *J. Acoust. Soc. Am* 1968;43:1267–1271. [PubMed: 5659495]

Adults

FIG. 1.

Masking functions showing total masking as a function of the number of masker components for each of the eight adult listeners in this study. Total masking is defined as the dB difference between the target threshold (75% correct in 2AFC) in quiet and in the presence of a masker. The horizontal lines represent total masking with a broadband noise masker. Solid symbols connected by solid lines (and the solid horizontal line) refer to masking with the ipsilateral masker. The open symbols connected by dashed lines (and the horizontal dashed line) refer to masking with the contralateral masker. The error bars around each data point represent the 95% confidence intervals determined by the bootstrapping technique described in the text. Each panel is labeled with the 3-letter listener code and the listener's age, given in decimal years. Note that the data from the ipsilateral condition are a reanalyzed version of the data shown in Oh *et al.* (2001).

Preschool Children

FIG. 2.
Same as Fig. 1, but for the listeners in the preschool group.

FIG. 3.

(a) Same as Fig. 1, but for the listeners in the younger school-age group. For these listeners, the data from the ipsilateral condition are a realayed version of the data shown in Lutfi *et al.* (2003). (b) Same as (a), but for the listeners in the older school-age group.

FIG. 4.

Mean masking functions for listeners in the four age groups. The meanings of the symbols and the solid and dashed lines are the same as in Fig. 1. However, the dash-dot lines are predictions of the CoRE model, and the s values are the scale factors discussed in the text. The error bars represent the 95% confidence intervals computed in the traditional way from the variance of individual threshold estimates, assuming they are normally distributed.