The monaural temporal window based on masking period pattern data in school-aged children and adults

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Several lines of evidence indicate that auditory temporal resolution improves over childhood, whereas other data implicate the development of processing efficiency. The present study used the masking period pattern paradigm to examine the maturation of temporal processing in normal-hearing children (4.8 to 10.7 yrs) compared to adults. Thresholds for a brief tone were measured at 6 temporal positions relative to the period of a 5-Hz quasi-square-wave masker envelope, with a 20-dB modulation depth, as well as in 2 steady maskers. The signal was a pure tone at either 1000 or 6500 Hz, and the masker was a band of noise, either spectrally wide or narrow (21.3 and 1.4 equivalent rectangular bandwidths, respectively). Masker modulation improved thresholds more for wide than narrow bandwidths, and adults tended to receive more benefit from modulation than young children. Fits to data for the wide maskers indicated a change in window symmetry with development, reflecting relatively greater backward masking for the youngest listeners. Data for children >6.5 yrs of age appeared more adult-like for the 6500- than the 1000-Hz signal. Differences in temporal window asymmetry with listener age cannot be entirely explained as a consequence of a higher criterion for detection in children, a form of inefficiency.

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I. INTRODUCTION

Auditory temporal resolution refers to the ability to detect and follow changes in acoustic stimuli over time. Studies have shown that children perform more poorly than adults on a range of temporal resolution tasks, including gap detection (Irwin *et al.*, 1985; Wightman *et al.*, 1989; Trehub *et al.*, 1995), amplitude modulation detection (Hall and Grose, 1994), and detection of a brief tone presented before or after a noise masker (e.g., Buss *et al.*, 1999; Hartley *et al.*, 2000). Some data indicate that the maturation of temporal processing may be frequency specific (Irwin *et al.*, 1985; Grose *et al.*, 1993; He *et al.*, 2010). For example, He *et al.* (2010) measured tone detection thresholds for a range of signal durations in school-aged children and adults. They reported an age effect in the amount of temporal integration at 1625 Hz, but not at 6500 Hz. Despite clear demonstrations of maturation in temporal processing, the factors responsible for these developmental trends are unknown. One possibility is that the period of compulsory integration is prolonged in children. Another possibility is that young children are less adept than adults at weighting auditory information in temporal processing tasks, or that their auditory processing is less efficient than that of adults in other respects (e.g., Hall and Grose, 1994; Hartley and Moore, 2002; Hill *et al.*, 2004). The present experiments attempt to distinguish among these alternatives.

Temporal processing is often characterized using a model that includes one or more auditory filters, a non-linearity (rectification and transformation to power), a sliding temporal integrator (temporal window), and a decision device (e.g., Viemeister, 1979; Moore *et al.*, 1988). Some implementations of this basic model also include amplitude compression prior to integration (Penner, 1979; Oxenham and Moore, 1994; Hill *et al.*, 2004). The shape and duration of the temporal window are thought to capture the key factors underlying auditory temporal resolution (Festen and Plomp, 1981; Moore *et al.*, 1988; Plack and Moore, 1990; Oxenham and Moore, 1994). In normal-hearing adults, temporal windows fitted to data for brief-tone detection in a temporally gapped masker tend to be asymmetric, with less attenuation of stimulus energy occurring before than after the temporal center of the window (Moore *et al.*, 1988). This asymmetry reflects relatively greater effects of forward than backward masking. The time constant of the monaural temporal window is sometimes reported as the equivalent rectangular duration (ERD), defined as the duration of a rectangular temporal window passing the same total energy. In normal-hearing adults, the ERD for detecting a brief tone in a temporally gapped masker has been reported to be on the order of 7 to 8 ms (Moore *et al.*, 1988), with modest effects of the stimulus level and signal frequency (Plack and Moore, 1990).

Temporal resolution can be characterized using a number of different psychoacoustic paradigms. However, the resulting estimates of the shortest resolvable stimulus feature differ by an order of magnitude or more across paradigms (Eddins and Green, 1995). For a multicomponent stimulus, for example, the threshold for detecting a delay in the onset of one component relative to the others is as low as 100 to 200 μs under some conditions (Zera and Green, 1993). In contrast, the time constant associated with detecting amplitude modulation or the introduction of a temporal gap in a

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broadband noise is on the order of 3 ms (Forrest and Green, 1987). Estimates of temporal resolution differ across paradigms but they can also depend on the stimulus parameters used within a particular paradigm. For example, Eddins *et al.* (1992) showed that the detection of a gap in a bandpass noise improves proportional to the square root of the noise bandwidth, irrespective of the frequency region of the stimulus. In that study, gap detection thresholds fell from 40 ms for a 50-Hz bandwidth to 5 ms for a 1600-Hz bandwidth. Two factors have been implicated in this bandwidth effect. One is the disruptive effect of the low-rate envelope fluctuation that characterizes narrowband noise stimuli, and the other is the opportunity for across-channel comparisons with wideband stimuli (Eddins and Green, 1995). The disparate estimates of temporal resolution obtained with different paradigms and stimuli highlights the fact that performance in these tasks is impacted by a number of interrelated factors, including peripheral factors (e.g., the fidelity of peripheral stimulus encoding), central factors (e.g., the combination of information across auditory channels), and stimulus factors (e.g., inherent noise fluctuation). Temporal windows fitted to data from a given paradigm and stimulus set may therefore differ from those associated with other paradigms and stimuli.

To date there have been only a few studies specifically investigating the development of the monaural temporal window in children. Hall and Grose (1994) measured amplitude modulation detection as a function of modulation rate in adults and three groups of children (4 to 5, 6 to 7, and 9 to 10 yrs). While younger children performed more poorly than older children and adults, the time constants fitted to the data indicated comparable temporal resolution across groups. It was argued that maturation of efficiency, rather than a peripherally-based limit on temporal resolution, could account for the age effects observed in that dataset. The idea was that the auditory periphery of children encodes the stimulus envelope with the same fidelity as in adults but that the more central auditory processes that make use of the temporal information conveyed by the envelope are less efficient. A wide range of factors could be responsible for reduced efficiency in children, including less focused auditory attention and non-optimal listening strategies. The effect of reduced efficiency is typically operationalized as an increase in the criterion associated with detection. In the case of modulation detection, this would entail a greater modulation depth at threshold.

Reduced efficiency has also been argued to play a causal role in the pronounced developmental effects observed in non-simultaneous masking (Hartley and Moore, 2002; Hill *et al.*, 2004). Hill *et al.* (2004) measured backward masking thresholds as a function of the signal-to-masker interval for a group of 9 to 10 year-old children and adults. Children had higher thresholds than adults overall, particularly for the shortest signal-to-masker interval. However, modeling indicated that these results could be explained as a consequence of reduced processing efficiency in children, in combination with compression. If children require a higher criterion signal-to-noise ratio (SNR) than adults to detect a signal, then threshold differences between groups could be greater for non-simultaneous than simultaneous masking conditions due to independent compression of the signal and masker. These modeling results were used to argue that prolongation of the temporal window is not required to account for the data of 9 to 10 year-olds.

While reduced efficiency provides a parsimonious account of the age effects in backward masking in the data of Hill *et al.* (2004), it is not clear whether it can account for developmental trends in non-simultaneous masking generally. Buss *et al.* (1999) measured thresholds for a brief, 1000-Hz signal presented before, during, or after a Gaussian noise masker that was 1200-Hz wide. Listeners were 5 to 11 year-olds and adults. Thresholds in that study improved with listener age in all conditions, but the slopes of lines fitted to child thresholds as a function of age were more than twice as steep in backward masking than in either forward or simultaneous masking. This difference in slopes was not significant but it suggests that age effects may be larger for backward than forward masking. Of interest with respect to efficiency, mean adult thresholds were slightly poorer in forward than backward masking conditions [43.3 and 41.6 dB sound pressure level (SPL), respectively], whereas the youngest children's thresholds tended to be better for forward than backward masking conditions. This result is not expected based on a model incorporating elevated criteria for detection in children, in combination with amplitude compression. For comparable signal levels, reduced efficiency would be expected to have comparable effects on thresholds in forward and backward masking conditions.[1] One goal of the present study was therefore to establish whether the non-significant trends observed by Buss *et al.* (1999) are reliable, and to examine the role of efficiency in forward and backward masking.

The procedure used in the present study to characterize the monaural temporal window was to measure detection thresholds for a brief signal at different temporal positions with respect to a quasi-square-wave masker envelope. The resulting pattern of thresholds, called the masking period pattern (MPP), was expected to closely follow the masker envelope to the extent that the auditory system is able to resolve energy associated with the signal from that associated with the fluctuating masker. Depending on the temporal position of the brief signal in the masker envelope, threshold in the MPP paradigm can reflect simultaneous and/or non-simultaneous masking. The MPP paradigm with square-wave modulation closely resembles the gapped-masker paradigm that Moore and his colleagues have used to estimate the temporal window (Moore *et al.*, 1988; Plack and Moore, 1990); in that paradigm, brief-tone thresholds are measured in a temporally gapped gated masker, whereas the MPP uses a continuous, fluctuating masker.

The MPP paradigm bears some resemblance to the method used in the developmental study of temporal resolution carried out by Grose *et al.* (1993). In that study, masked thresholds were measured in a steady or 10-Hz square-wave amplitude-modulated masker. The signal was a 400-ms pure tone at either 500 or 2000 Hz, and maskers were Gaussian noise bands centered on the signal frequency, having bandwidths of either 76 or 240 Hz. Detection thresholds were compared between steady and modulated masking noise, and the difference was interpreted in terms of temporal resolution. This approach, sometimes referred to as the "modified MPP" (Zwicker and Schorn, 1982), rests on the idea that thresholds are determined by the peak SNR in the internal representation of the stimulus. Sensitivity to the signal is thought to reflect the fidelity with which the auditory system follows temporal fluctuations in SNR. Grose *et al.* (1993) found that young children showed a reduced ability to benefit from masker modulation. This effect was larger for the 500-Hz than the 2000-Hz signal frequency, and larger for the 76-Hz than the 240-Hz masker bandwidth. Grose *et al.* (1993) hypothesized that narrow masker bandwidths could be associated with higher processing demands than wide masker bandwidths due to the absence of across-channel masker envelope cues, which can help differentiate the signal from the masker (Puleo and Pastore, 1980; Moore and Glasberg, 1982; Hall *et al.*, 1984).

The present study investigated the development of the monaural temporal window using the MPP paradigm. It was hypothesized that school-aged children would show greater developmental effects for backward than forward masking. Temporal resolution was expected to mature at an earlier age for high than low signal frequencies, and children were expected to perform more poorly with the narrowband than the wideband masker relative to adults.

II. EXPERIMENT

In the MPP paradigm, thresholds are expected to closely follow the masker envelope to the extent that the auditory system is able to resolve energy associated with the brief signal from that associated with the fluctuating masker. One reason for using the MPP to study temporal processing in children is that it allows for a test of whether the findings of Grose *et al.* (1993), using long signals, also pertain for short signals. This is of interest in light of recent data indicating that children may be particularly poor at detecting a *short* signal presented in close temporal proximity to an abrupt change in masker level (He *et al.*, 2010). The MPP is well suited for examining differential effects of forward and backward masking at several different signal delays relative to an abrupt change in masker level. Most previous studies with children have used a single delay, with the notable exception of the backward masking data collected by Hill *et al.* (2004). Data using the MPP method support an estimate of both temporal window duration and asymmetry, as well as efficiency.

A. Methods

1. Listeners

Potential listeners were screened for normal hearing sensitivity, defined as pure-tone detection thresholds of 20 dB hearing level or better at octave frequencies from 250 to 8000 Hz (ANSI, 2004). None of the listeners had a history of chronic ear disease or a history of speech, language, or learning disorders, as assessed by self or parental report. All listeners were paid an hourly rate for participation.

Child listeners were initially recruited to uniformly span the ages of 5 to 10 yrs. Analysis of initial data, however, revealed a natural breakpoint in the data pattern at around 6.5 yrs. This observation initiated additional data collection with children younger than 6.5 yrs, to facilitate comparison of children below and above that age. The final data for each sub-experiment included 7 children younger than 6.5 yrs, 9 or more children older than 6.5 yrs, and 10 adults in each condition of each experiment. Table I shows the mean listener age and the listener count in each sub-experiment. A sub-experiment was composed of thresholds for a fixed signal frequency and masker bandwidth. Some listeners participated in more than one sub-experiment: On average, children completed 1.7 sub-experiments and adults completed 1.1 sub-experiments. Care was taken to balance the number of naive and experienced listeners in each age group and in each sub-experiment. For an individual listener, data in one sub-experiment were collected within a two-week period but participation in different sub-experiments could be separated by up to 2 yrs (median of 6 months).

2. Stimuli

The signal was a pure tone, ramped on and off with no steady state. The masker was either a stationary (*steady*) or amplitude-modulated (*AM*) bandpass-filtered Gaussian noise sample that played continuously over the course of a threshold estimation track. In *steady* conditions, the masker was presented at either 55 or 75 dB SPL, referred to as *steady-low* and *steady-high* conditions, respectively. These levels represent the masker level in the envelope minimum and maximum of the *AM* masker. A 20-dB modulation depth was chosen in order to avoid effects related to absolute threshold. In the *AM* conditions, the masker level alternated between 55 and 75 dB SPL every 100 ms, with ramps smoothing these transitions. This resulted in a 5-Hz modulation rate. Detection thresholds in the *AM* masker were measured at six time points in the masker envelope. These conditions were defined in terms of the delay between the temporal center of a masker modulation maximum and the temporal center of the brief signal. These signal delays were 58, 79, 100, 121, 142, and 200 ms.[2] Figure 1 illustrates the timing of each signal relative to the masker envelope in the *AM* conditions.

TABLE I. Mean listener age in years and listener count for each of three age groups in the four sub-experiments.

Masker bandwidth	Signal frequency	Child <6.5 yrs	Child >6.5 yrs	Adult
Narrow (1.4 ERBs)	6500 Hz	5.6 $n = 7$	7.6 $n = 12$	27.7 $n = 10$
	1000 Hz	5.6 $n = 7$	7.9 $n = 9$	34.1 $n = 10$
Wide (21.3 ERBs)	6500 Hz	5.7 $n = 7$	7.9 $n = 12$	32.9 $n = 10$
	1000 Hz	5.8 $n = 7$	8.1 $n = 9$	31.1 $n = 10$

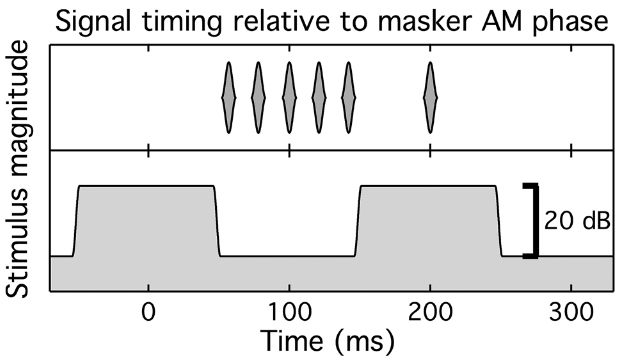

FIG. 1. Temporal properties of signal and masker stimuli in the *AM* conditions are illustrated. The top panel shows signals in each of six delay conditions. The associated pattern of masker modulation is illustrated in the bottom panel. Both signal and masker level transitions are smoothed using 5-ms raised-cosine ramps; this duration was used in all conditions except the narrow masker condition at 1000 Hz.

Variables that differed across sub-experiments are defined in Table II. These variables include signal frequency, masker bandwidth, and the ramp duration used for gating the signal and for smoothing masker transitions. Signal frequencies were 1000 and 6500 Hz. Maskers were either wide or narrow. The wide masker spanned 500 to 7000 Hz, which corresponds to 21.3 equivalent rectangular bandwidths (ERBs; Glasberg and Moore, 1990). The narrow masker was centered on the signal and was 1.4 ERBs wide (909 to 1093 Hz or 6000 to 7000 Hz). In most conditions, the ramps used for gating the signal and smoothing masker envelope transitions were 5-ms raised cosines. For the narrow masker and 1000-Hz signal, however, the ramps were 27.5-ms raised cosines. This duration was chosen to prevent spectral splatter outside the masker passband from serving as a cue to the presence of the signal for the narrowest masker bandwidth. The splatter associated with signal gating was at least 50-dB down at the spectral edges of the masker band in all conditions.

Stimuli were generated using a custom MATLAB script and a real-time processor (RP2, TDT) that controlled stimulus gating and signal generation. Maskers were generated in the frequency domain, with 2^{18} points and a 24.4-kHz sampling rate. This resulted in a 10.7-s sample that repeated seamlessly. Stimuli were routed from the output of the real-time processor to a headphone buffer and then presented monaurally to the left earphone of a Sennheiser (Wedemark, Germany) HD 265 headset.

3. *Psychophysical procedures*

Trials were presented as a three-alternative forced-choice, with both listening intervals and inter-stimulus intervals lasting 400 ms. Threshold estimates were obtained using a two-down one-up adaptive strategy, estimating 70.7% correct on the psychometric function (Levitt, 1971). Initial signal level adjustments were made in steps of 4 dB. This step size was reduced to 2 dB after the second track reversal. A threshold track stopped after eight reversals, and the signal level at the final six reversals was averaged. Threshold estimates were obtained blocked by condition, with conditions run in quasi-random order for each listener. At least three threshold estimates were obtained for each condition, with a fourth collected in cases where the first three spanned a range of 3 dB or more.

TABLE II. Stimulus parameters used in each sub-experiment.

	Signal frequency	Masker band	Ramp duration
Narrow	6500 Hz	6000 to 7000 Hz	5 ms
(1.4 ERBs)	1000 Hz	909 to 1091 Hz	27.5 ms
Wide	6500 Hz	500 to 7000 Hz	5 ms
(21.3 ERBs)	1000 Hz	500 to 7000 Hz	5 ms

Listening intervals were marked visually using animation on a computer screen. A cartoon picture was revealed over the course of a track, in the style of a jigsaw puzzle, with one piece revealed following each correct response. The puzzle display remained unchanged following an incorrect response. A progress bar at the top of the screen indicated the number of track reversals obtained. At the end of a track the puzzle was completed, and the underlying image performed a 2-s animation. All listeners used this interface. Testing took place in a double-walled sound-attenuating booth.

Data were assessed with respect to assumptions of normality, homogeneity of variance, and sphericity prior to analysis. Non-parametric statistics were used as indicated. Tests were two-tailed unless otherwise indicated, and a significance criterion of $\alpha = 0.05$ was adopted. In all analyses, signal frequency and masker bandwidth were between-listener variables. While many listeners participated in more than one set of conditions, this participation was often separated by months or years, and in several cases children were in the <6.5 yrs age group for the first set of conditions and the >6.5 yrs age group for the second set of conditions. It was therefore decided not to treat these data sets as repeated measures. Each statistical analysis included data from only one sub-experiment of each listener, leading to the exclusion of 7% to 12% of the data from analysis.[3] Figures show all the data that were collected.

4. *Fitting procedures*

Temporal window parameter estimates were obtained using procedures similar to those used in previous studies (Moore *et al.*, 1988; Plack and Moore, 1990; Hill *et al.*, 2004). In this modeling approach, the stimulus power passed by an auditory filter is convolved with a temporal window. Thresholds in each condition are estimated using a criterion value for the peak SNR in the time-domain output. Using the peak SNR, rather than the SNR centered on the signal, captures the benefits of off-time listening that are present under some conditions. This procedure allows an estimate of the ERD and asymmetry of the temporal window, as well as the criterion SNR associated with threshold.

In the present analysis, the quasi-square-wave envelope was assumed to represent masker level, ignoring inherent modulations of the noise carrier. Effective masker level at the output of an auditory filter was estimated using the ERB (Glasberg and Moore, 1990) at the signal frequency for each set of conditions. Arrays associated with the masker and signal-plus-masker were squared and convolved with a temporal window, each edge of which was defined as

$$W(t) = (1 + 2t/Tp)\exp(-2t/Tp). \quad (1)$$

The function W is the weighting function describing the window shape, t is the time interval to the midpoint of the window (in ms), and Tp characterizes the sharpness of the window edge. This procedure results in two values of Tp, corresponding to weights applied to stimulus events before and after the midpoint of the window. These values are reported below as Tp_b and Tp_a, respectively. In some analyses a compressive non-linearity was introduced prior to convolution with the temporal window. Following Hill *et al.* (2004), this was defined by the equation

$$y = 0.9x + 15.8 + 53.05\left(1 - \frac{1}{1 + \exp(-0.05(x - 50))}\right), \quad (2)$$

where x and y are the levels, in dB, of the stimulus before and after compression, respectively. In all cases—with or without compression—the output of the temporal window is defined here as the temporal excitation pattern (TEP).

Thresholds were predicted using this model for all eight conditions in a sub-experiment: The six *AM* masker conditions and the two *steady* masker conditions. For each of these conditions, the peak SNR was determined for a range of signal levels by comparing the TEP for masker alone with the TEP for each signal-plus-masker stimulus. The lowest signal level in that range was associated with a peak SNR that was at least a factor of 2 below the criterion SNR, and the highest with a peak SNR that was at least a factor of 2 above the criterion SNR; levels within this range were separated by 2 dB. The signal level associated with the criterion SNR was then determined using a spline fit. Parameter fits to the data were made using the *fminsearch* procedure in MATLAB, with Tp_b, Tp_a, and criterion SNR free to vary. This procedure minimized the sum of squared errors of the threshold estimates. Both Tp_b and Tp_a were restricted to values of 1 ms or greater, and the criterion SNR was restricted to values of 0.1 dB or greater; the best-fitting parameter estimates were well above these limits in all cases.

The predicted effects of elevated criteria for detection in children, in combination with amplitude compression, are demonstrated in Fig. 2. Thresholds shown here were predicted based on a model incorporating compression. The stimulus was the 6500-Hz signal and wide masker, and the parameters describing the shape of the temporal window were fixed at values associated with adult data in this condition.[4] The criterion SNR was varied over the range associated with predicted thresholds above and below those observed in individual listeners' data, as described below. Threshold predictions associated with each criterion are shown as solid lines, and the shaded area indicates the masker envelope shape, arbitrarily shifted along the ordinate for illustrative purposes. Figure 2 shows that changing the criterion had a greater effect on thresholds for signals in the envelope minimum than those in the maximum. However, the asymmetry of the threshold function was preserved with increasing criterion. In this example, forward masking was approximately 2.2 times greater than backward masking regardless of criterion. Using this modeling approach, a change in temporal window asymmetry with age cannot be attributed to changes in efficiency.

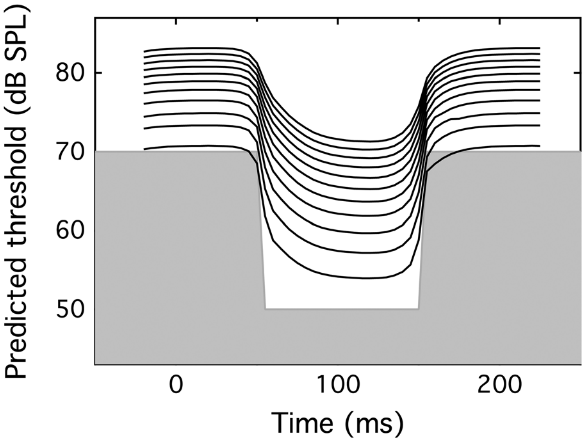

FIG. 2. Threshold estimates are shown for a fixed temporal window and a range of criteria. The stimulus was a 6500-Hz signal and a wide masker, and the temporal window parameters were based on fits to adult data. The shaded area indicates the masker envelope, arbitrarily shifted along the ordinate.

B. Psychophysical results

Mean thresholds for the narrowband masker are shown in Fig. 3, and those for the wideband masker are shown in Fig. 4. The standard deviations of these threshold estimates were relatively consistent across age groups and signal frequency, with median values ranging from 1.6 to 3.3 dB. Thresholds for the 1000-Hz signal appear on the left in each figure, and those for the 6500-Hz signal appear on the right. Within each column, the left portion of each panel shows thresholds for the *steady-high* and *steady-low* conditions, and the right portion shows thresholds in the *AM* conditions, plotted as a function of the temporal position of the signal. Symbol shapes reflect the listener age group, as indicated in the legend. The shaded area indicates the temporal properties of the masker envelope, arbitrarily shifted along the ordinate so that the peak envelope value corresponds to the mean *steady-high* threshold for adults. Lines in Fig. 4 indicate threshold estimates based on temporal window fits to the mean data in each group, as discussed below. Results for the two masker bandwidths are considered separately.

1. Narrowband masker conditions

Thresholds in the *steady* narrowband masker tended to be poorest for the youngest listeners. Age effects were evaluated using a repeated-measures analysis of variance (ANOVA) on the *steady* masker thresholds, including the within-subjects factor of masker level (low, high), and the between-subjects factors of age group (<6.5 yrs, >6.5 yrs, adults), and signal frequency (1000 Hz, 6500 Hz). There was a main effect of masker level ($F(1,44) = 2862.15$, $p < 0.001$), signal frequency ($F(1,44) = 46.84$, $p < 0.001$) and age group ($F(2,44) = 22.04$, $p < 0.001$). None of the interactions with

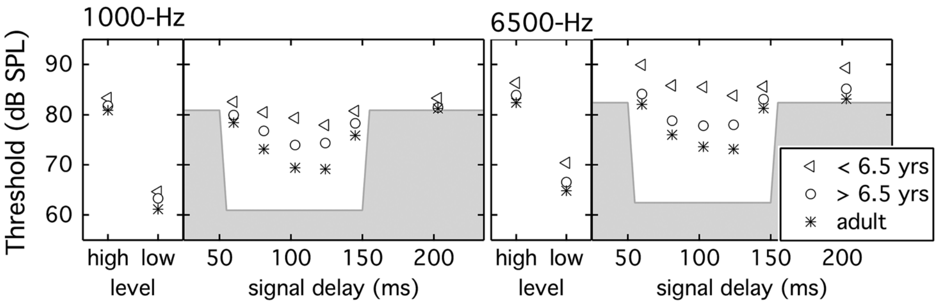

FIG. 3. Mean detection thresholds for signals in the narrowband masker are plotted for each age group. Results for the 1000-Hz signal are shown in the left column, and those for the 6500-Hz signal are shown in the right column. Symbols reflect listener age group, as defined in the legend. Results for the *steady* masker conditions appear at the left of each panel, plotted for the low (55 dB SPL) and high (75 dB SPL) masker levels. Results for the *AM* masker conditions appear at the right of each panel, plotted as a function of signal delay. The shaded area indicates the *AM* masker envelope, shifted along the ordinate so that the peak envelope value corresponds to the associated *steady-high* threshold for adults.

group were significant ($p > = 0.15$), but there was a significant interaction between masker level and signal frequency ($F(1,44) = 9.29$, $p = 0.004$). This interaction reflects the fact that the growth of masking was somewhat shallower at the 6500- than the 1000-Hz signal frequency. Across listener groups, the mean difference between thresholds in the *steady-low* and *steady-high* conditions was 19.1 dB for the 1000-Hz signal and 17.0 dB for the 6500-Hz signal. The absence of a three-way interaction ($F(2,44) = 0.64$, $p = 0.53$) indicates that frequency-specific growth of masking did not differ significantly between listener groups.

Thresholds in the *AM* masker tended to be higher for younger listeners, and this age effect was larger for signals coincident with the modulation minimum than maximum. Whereas thresholds were lower for signals in the temporal center of a masker modulation minimum than in a modulation maximum, this effect was modest compared to the 20-dB masker modulation depth. For children <6.5 yrs, thresholds for signals in the narrowband masker spanned a range of 5.5 dB for the 1000-Hz signal and 5.4 dB for the 6500-Hz signal. For adults, these values were 12.1 and 10.0 dB, respectively.

The ability to benefit from the introduction of modulation minima can be assessed by comparing performance for a signal in the minimum of the *AM* masker with that in the *steady-low* masker condition. In this analysis, the lowest mean *AM* threshold for each age group and signal frequency was identified for comparison with *steady-low* thresholds; the signal delay associated with the minimum threshold was allowed to differ across groups in order to accommodate possible group differences in temporal window shape. The difference between *steady-low* and the minimum threshold in the *AM* masker were then computed for individual listeners. Difference scores were evaluated with a Univariate ANOVA, including the factors age group (<6.5 yrs, >6.5 yrs, adult) and signal frequency (1000 Hz, 6500 Hz). There was a main effect of age group ($F(2,44) = 6.14$, $p = 0.004$), no effect of signal frequency ($F(1,44) = 0.07$, $p = 0.794$), and no interaction ($F(2,44) = 0.02$, $p = 0.983$). Contrasts indicated that children <6.5 yrs differed significantly from both children >6.5 yrs ($p = 0.032$) and adults ($p = 0.001$) but that children >6.5 yrs did not differ from adults ($p = 0.176$). This supports the observation that the youngest listeners appeared to benefit less from masker modulation than adults.

Repeating this analysis on the difference between thresholds for the 200-ms signal delay in the *AM* masker and thresholds in the *steady-high* masker conditions resulted in an effect of signal frequency ($F(1,44) = 7.09$, $p = 0.011$), no effect of age group ($F(2,44) = 1.25$, $p = 0.296$), and no interaction ($F(2,44) = 1.54$, $p = 0.226$). The effect of signal frequency reflects the fact that thresholds in *steady-high* masker and the maxima of the *AM* masker are similar for the 1000-Hz signal, whereas thresholds in the maxima of the *AM* masker are on average 1.5 dB higher than those in the steady masker for the 6500-Hz signal. The lack of an age effect in this analysis confirms that age effects in the MPP are dominated by differences in the ability to benefit from *AM*, as opposed to disruptive effects of *AM* for signals coincident with the masker modulation maxima.

2. *Wideband masker conditions*

As observed with the narrowband masker data, thresholds in the wideband *steady* masker conditions tended to improve with listener age. This effect was evaluated using a repeated-measures ANOVA on the *steady* masker

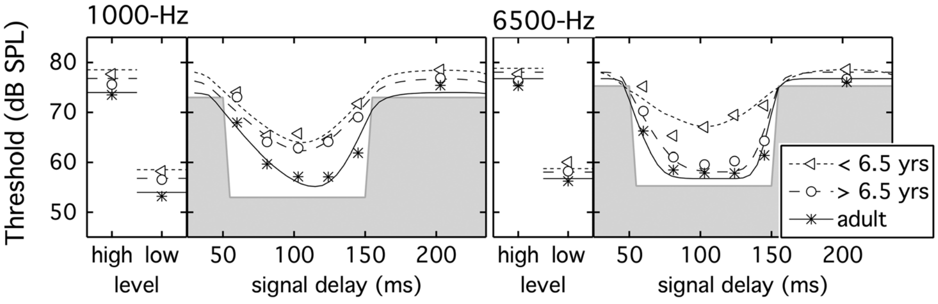

FIG. 4. Mean detection thresholds for signals in the wideband masker are shown, following the conventions of Fig. 2. The lines indicate fits to the mean data from each listener group, as defined in the legend.

thresholds, including the within-subjects factor of masker level (low, high), and the between-subjects factors of age group (<6.5 yrs, >6.5 yrs, adults), and signal frequency (1000 Hz, 6500 Hz). There were main effects of masker level ($F(1{,}44) = 5866.31$, $p < 0.001$), signal frequency ($F(1{,}44) = 17.90$, $p < 0.001$), and age group ($F(2{,}44) = 27.77$, $p < 0.001$). None of the interactions with group were significant ($p \geq 0.103$), but there was a significant interaction between the masker level and signal frequency ($F(1{,}44) = 8.89$, $p = 0.005$). As in the narrowband data, this interaction reflects the fact that the growth of masking was somewhat shallower at the 6500- than the 1000-Hz signal frequency. The mean difference between thresholds in the *steady-low* and *steady-high* conditions was 19.7 dB for the 1000-Hz signal and 18.3 dB for the 6500-Hz signal. While this difference was not predicted, the absence of a three-way interaction ($F(2{,}44) = 0.03$, $p = 0.974$) indicates that this result is unlikely to influence estimates of temporal resolution across age groups.

The pattern of signal detection thresholds in the *AM* conditions tended to reflect the pattern of the masker envelope in all three age groups, with lower thresholds during the modulation minima than maxima. The extent to which thresholds varied as a function of the temporal position of the signal differed across age groups, however. For the children <6.5 yrs, mean thresholds differed across the six signal positions by 14.0 and 13.3 dB at 1000 and 6500 Hz, respectively. In contrast, mean thresholds of adults differed by 18.3 and 18.2 dB, respectively. These ranges are 7 to 8 dB larger than those for the narrowband masker for both age groups. Thresholds were highest for the youngest listeners at all signal delays, but this difference was largest in the temporal center of the masker modulation minimum.

The difference between thresholds in the *steady-low* condition and the *AM* condition with the lowest group mean threshold was computed for each individual listener, and these values were submitted to a Univariate ANOVA with three levels of age group (<6.5 yrs, >6.5 yrs, adult) and two levels of signal frequency (1000 Hz, 6500 Hz). This analysis resulted in a main effect of age group ($F(2{,}44) = 3.84$, $p = 0.029$) and a main effect of signal frequency ($F(1{,}44) = 6.48$, $p = 0.014$), reflecting relatively lower thresholds in the *AM* minima for the 6500-Hz than the 1000-Hz signal. There was no interaction between signal frequency and group ($F(2{,}44) = 0.85$, $p = 0.432$). Contrasts indicated that children <6.5 yrs differed significantly from both children >6.5 yrs ($p = 0.042$) and adults ($p = 0.010$) but that children >6.5 yrs did not differ from adults ($p = 0.548$).

While the listener groups differed substantially in the ability to benefit from masker modulation, the effect of masker modulation on detection of signals in masker modulation maxima was very modest and uniform across age groups. A Univariate ANOVA was performed on the difference between thresholds for the 200-ms signal delay in the *AM* masker and *steady-high* thresholds. There was no main effect of listener age group ($F(2{,}44) = 0.66$, $p = 0.520$) or signal frequency ($F(1{,}44) = 1.54$, $p = 0.221$), and no interaction between signal frequency and group ($F(2{,}44) = 0.72$, $p = 0.492$). On average, thresholds in the *steady-high* and 200-ms signal delay conditions differed by 1.0 dB.

These analyses demonstrate differences across groups in the degree to which thresholds in the *AM* minima match those in the *steady-low* masker but not in the degree to which thresholds in the *AM* maxima match those in the *steady-high* masker. This is broadly consistent with a modeling approach based on a sliding integration window. In this class of models, signals presented during brief masker modulation minima are expected to suffer due to the inclusion of energy before and after presentation of the signal in the integration window, so differences in the shape or duration of the window would have an impact on thresholds. In contrast, signals presented during modulation maxima are expected to be affected less by temporal resolution. One aspect of the data that is not consistent with the model is the finding that the mean threshold obtained in the *AM* masker maxima is 1 dB worse than that obtained in the *steady-high* masker. This result indicates some cost associated with introducing dynamic changes in the masker level, which is not incorporated into the model. This effect is small relative to the effects of interest (i.e., the MPP) and does not appear to differ across age groups.

C. Fits to wideband masker data

Temporal window fits were performed on mean thresholds collected in the wideband masker for each age group and signal frequency, as well as thresholds for individual listeners. The decision not to fit the narrowband masker data was based on the observation that the effect of signal delay in the narrowband *AM* masker was small relative to the standard deviation of the mean thresholds, particularly for children <6.5 yrs. In the narrowband data for children <6.5 yrs, the MPP varied by less than $\sim$1.8 times the median standard deviation across listeners and less than 3.3 times the median standard deviation across estimates within a listener. This small effect size would tend to make data fits variable and unreliable.

Fits to mean wideband masker data using the model incorporating compression accounted for 80.4% to 95.6% of the variance in the mean data, and those to individual listeners' data accounted for 57.5% to 96.9% of the variance. Interestingly, a linear fit that omitted the compressive transformation described in Eq. (2) tended to provide a better fit to the data than the compressive model. Quantified as the difference between R^2 values, the linear fit out-performed the non-linear fit by 13.1% (children <6.5 yrs), 8.5% (children >6.5 yrs), and 5.2% (adults). Estimates of the ERD, criterion SNR, and temporal window asymmetry based on fits with and without non-linear compression produced the same general pattern of results. The better (linear) fits are therefore reported below.

The fits to mean data using a linear model are shown in Fig. 4, with line style reflecting the listener group, as defined in the legend. The parameter values associated with these fits appear in Table III. These values were used to estimate the ERD, obtained by integrating the area under the double exponential window, and temporal window asymmetry,

TABLE III. Results of temporal window fits to mean thresholds in the wide masker for each age group. Parameters Tp_b and Tp_a are the time constants associated with stimulus energy occurring before and after the temporal midpoint of the signal, in ms. The criterion is the SNR associated with threshold at the output of the temporal window, in dB. The quality of the fit was assessed with R^2. Results are shown for data fits without compression.

		Fitted parameters			
Stimulus sig freq/bw	Age group	Tp_b	Tp_a	crit	R^2
6500 Hz	<6.5 yrs	27.8	23.7	4.0	92.0
Wide	>6.5 yrs	11.7	5.9	6.8	97.1
	Adult	7.8	4.5	6.9	98.5
1000 Hz	<6.5 yrs	23.0	17.8	10.5	96.8
Wide	>6.5 yrs	23.1	18.0	9.0	97.1
	Adult	18.0	9.6	8.0	97.9

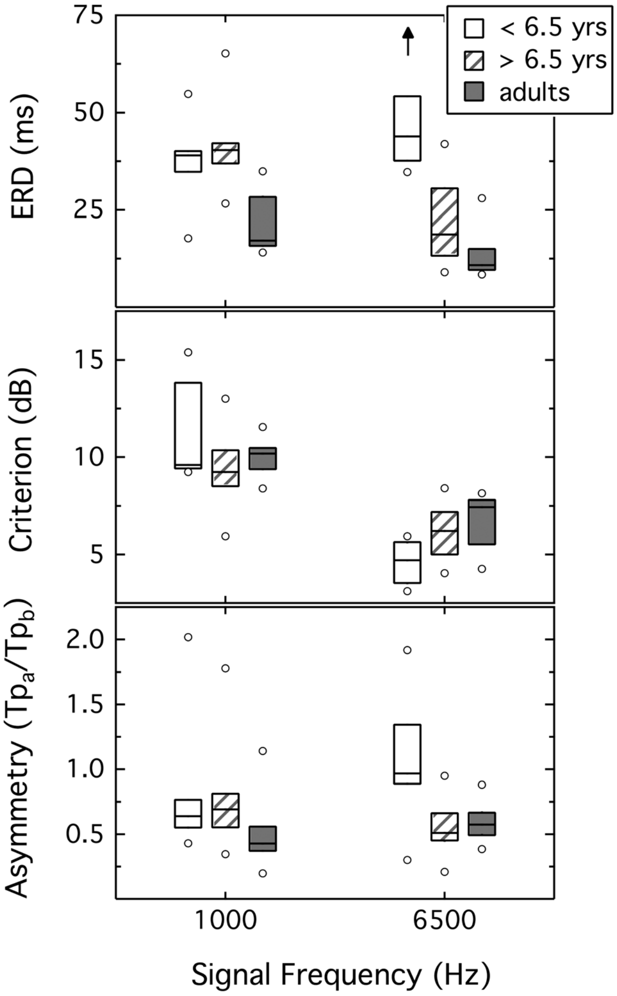

FIG. 5. The distribution of temporal window parameters based on fits to individual data from the wideband masker conditions. Results are shown separately for each age group and signal frequency. Estimates of temporal window ERD (in ms) are shown in the top panel, criteria at threshold are shown in the middle panel, and values of Tp_a/Tp_b, quantifying window asymmetry, are shown in the bottom panel. Bar fill reflects listener group, as defined in the legend. Bars span the 25th to 75th percentiles, horizontal bars indicate the median, and circles show the extreme values in each distribution. The up-pointing arrow indicates that the maximum value exceeded the maximum ordinate value.

computed as the ratio Tp_a/Tp_b. Temporal window fits to individual data were used to evaluate the significance of differences in fits to mean data for each of the age groups. Estimates of the ERD, SNR criterion, and Tp_a/Tp_b obtained from fits to individual listeners' data were used to generate the box plots in Fig. 5. Boxes span the 25th to 75th percentiles, with horizontal lines indicating the median value; circles show the maximum and minimum values. Results are plotted separately for the two signal frequencies, and the bar fill indicates listener age group, as defined in the legend.

1. *Estimates of ERD and criterion*

The top panel of Fig. 5 shows that the ERD tends to be shorter for older listeners. The ERD for children <6.5 yrs is consistently larger than that for adults, with mean differences of 15.6 and 34.1 ms for the 1000- and 6500-Hz signal frequency, respectively. The ERDs for children >6.5 yrs resembled those for the youngest group for the 1000-Hz signal, but they are closer to the adult ERDs for the 6500-Hz signal. These trends were assessed with a Univariate ANOVA on the logarithm of the ERD in ms. There were three levels of age group (<6.5 yrs, >6.5 yrs, adult) and two levels of signal frequency (1000 Hz, 6500 Hz). There was a main effect of the listener group ($F(2,44) = 22.54$, $p < 0.001$), an effect of signal frequency ($F(1,44) = 7.90$, $p = 0.007$), and a significant interaction between group and frequency ($F(2,44) = 5.62$, $p = 0.007$). Simple effects tests were performed to better understand this interaction. For the 1000-Hz signal data, ERDs were significantly smaller for adults than for children <6.5 yrs ($p = 0.007$) and children >6.5 yrs ($p = 0.003$), but the two groups of children did not differ ($p = 0.81$). For the 6500-Hz signal data, ERDs were larger for children <6.5 yrs than children >6.5 yrs ($p < 0.001$) and larger for children >6.5 yrs than adults ($p = 0.003$). Like the previous analysis of *AM* threshold differences, these results are broadly consistent with the idea that development of temporal resolution is accelerated at 6500 Hz relative to 1000 Hz. Interpretation of these results depends critically on the criterion SNR at threshold, however.

The middle panel of Fig. 5 shows the fitted values of criterion, which is thought to reflect listener efficiency. The expectation was for criterion SNR to fall with increasing listener age, but this expectation was not met. Estimates of criterion were relatively consistent across age groups for both the 1000-Hz and the 6500-Hz signal frequency. This was supported by a pair of Kruskal-Wallis tests, with three levels of listener age group (<6.5 yrs, >6.5 yrs, adults). Results indicate no effect of age for either the 1000-Hz signal ($\chi^2(2) = 3.07$, $p = 0.215$) or the 6500-Hz signal ($\chi^2(2) = 5.37$, $p = 0.068$). The non-significant trend in this second analysis is not in the predicted direction. The relatively small estimates of criterion SNR in the youngest listeners could be due to a failure to fit some aspects of the data pattern obtained. Consider thresholds for the 6500-Hz signal in the wideband masker (Fig. 4, right panel). In this subexperiment, thresholds for the 58- and 79-ms delays (the first two points to the left) are not well fitted for the youngest listeners; the threshold for the 58-ms delay is underestimated and the threshold for the 79-ms delay is over-estimated. The relatively rapid decay of forward masking between 58 and 79 ms is not captured in the data fit, perhaps due to the fact that relatively little decay has occurred by the 58-ms delay point. The solution converged upon by the model was a relatively long ERD, associated with a more gradual decay of forward masking. This relatively long ERD admits more masking energy than a shorter ERD, driving down the criterion at threshold. By this scenario, poor fits to the data could result in elevated estimates of ERD and (consequently) depressed estimates of criterion SNR.

If values of criterion were depressed due to elevated ERDs, then there should be a negative correlation between these two parameters. This was assessed by computing a Spearman's rank-order correlations for each age group, with data collapsed across the two signal frequencies. Assessing the results using a one-tailed criterion, there was a negative correlation between estimates of the ERD and criterion for children <6.5 yrs ($\rho = -0.50$, $p = 0.041$) but not for children >6.5 yrs ($\rho = -0.01$, $p = 0.479$) or adults ($\rho = 0.23$, $p = 0.168$). This result suggests that the interrelation between estimates of the ERD and criterion could affect parameter estimates for the youngest group of listeners.

2. *Estimates of asymmetry and effects of compression*

The bottom panel of Fig. 5 shows the ratio of the time constants defining the lagging and leading edges of the temporal window (Tp_a/Tp_b), an estimate of temporal window asymmetry. If the window was perfectly symmetrical, this ratio would be 1.0. A value less than 1.0 indicates relatively more forward masking, and a value greater than 1.0 indicates relatively greater backward masking. In most cases the value associated with the 75th percentile falls well below 1.0, with the exception of the youngest listener group and the 6500-Hz signal. In this group, some listeners' data are consistent with relatively greater forward masking (as in the other listener groups), some with approximately equal forward and backward masking, and some with relatively greater backward masking. A Univariate ANOVA was performed to assess the significance of these trends in the data. A log transform was applied to ensure equality of error variance. This analysis resulted in a main effect of the listener group ($F(2,44) = 3.75$, $p = 0.031$), no effect of signal frequency ($F(1,44) = 0.04$, $p = 0.841$), and no interaction between group and frequency ($F(2,44) = 1.92$, $p = 0.159$). Contrasts indicated that children <6.5 yrs differed significantly from both children >6.5 yrs ($p = 0.040$) and adults ($p = 0.011$) but that children >6.5 yrs and adults did not differ ($p = 0.605$).

In light of the observation that poor fits to the data may have resulted in elevated estimates of ERD and depressed estimates of criterion, it is worth considering whether the estimates of asymmetry accurately reflect the pattern of psychophysical thresholds. Based on fits to the data collected at the 6500-Hz frequency, it appears as if the trends of forward and backward masking were well captured by the model, with the exception of thresholds associated with the 58- and 79-ms signal delays in children <6.5 yrs. The data fit overpredicts thresholds at the 79-ms signal delay by 3.9 dB. Whereas the fit is consistent with a minimum threshold for the 100-ms signal delay, the lowest threshold occurred for the 79-ms delay in more than half of the children <6.5 yrs. This observation suggests that if anything, the present fits underestimate the degree to which backward masking exceeded forward masking in this group.

3. *Fits assuming a consistent temporal window across age*

While the temporal window fits to the data differed across age groups, it is of interest to determine the extent to which the window fitted to adult data accounts for data of children <6.5 yrs. Mean data of children <6.5 yrs were fitted with the time constants (Tp_a and Tp_b) fixed at the values appropriate for adult data, and the criterion was left as a free parameter. Fits in which just the criterion was free to vary accounted for 88.8% and 54.5% of the variance for signals of 1000 and 6500 Hz. This can be compared to values of 96.8% and 92.0% for fits in which all three parameters were allowed to vary. If the temporal window is the same for adults and children <6.5 yrs, then for a linear model the threshold difference across groups in the steady masker is a direct reflection of the criterion. Thresholds for the steady wideband maskers differed across groups by 4.6 and 3.1 dB for the 1000- and 6500-Hz signals, respectively. The model in which only the criterion was free to vary converged on values of criterion that were nearly 10 dB higher than expected, with values of 13.7 and 13.0 dB, respectively. While the finding of better fits with a model having more free parameters is not surprising, the magnitude of the criterion in the constricted fit suggests that the temporal window derived with the standard model used here differs across groups.

III. GENERAL DISCUSSION

The present study used the MPP paradigm to assess the maturation of temporal resolution. The experiments reported here examined this ability at two signal frequencies, 1000 and 6500 Hz. There were two masker bandwidths, narrow (1.4 ERBs) and wide (21.3 ERBS), and modulation was 5-Hz quasi-square wave, with a 20-dB modulation depth. These data were used to evaluate three hypotheses: (1) That temporal resolution matures over the age range tested, with greater developmental effects for backward than forward masking; (2) that thresholds from young children are more adult-like for high- than low-frequency signals; and (3) that temporal resolution of children is particularly poor in narrowband masking noise.

A. Temporal resolution as a function of age

The ERDs fitted to adult data were substantially longer than those reported by Moore and his colleagues (Moore *et al.*, 1988; Plack and Moore, 1990). That previous work reported ERDs of 7 to 8 ms at 500 and 2000 Hz, but the ERD at 1000 Hz for the wideband masker in the present study was 12.4 ms; discrepancies were even larger at the 6500-Hz frequency. While stimulus factors could play a role in this discrepancy—particularly the use of a continuous modulated masker with a 20-dB modulation depth—it is also possible that listening experience was an important factor. The adult listeners in the present study were naive at the outset, whereas data from Moore *et al.* (1988) were collected from the first two authors and one other listener.

The mean data of younger listeners exhibited greater non-simultaneous masking than those of older listeners at both signal frequencies and with both masker bandwidths. This was quantified in terms of the difference between thresholds in the *steady-low* and the minimum threshold in the *AM* masker, in terms of the range of thresholds observed in the *AM* masker, and in terms of the ERD based on fits to the wideband masker data. This result is broadly consistent with previous results showing a developmental effect in tasks relying on temporal resolution (Irwin *et al.*, 1985; Wightman *et al.*, 1989; Grose *et al.*, 1993; Hall and Grose, 1994), including studies of non-simultaneous masking (Hartley *et al.*, 2000; Hill *et al.*, 2004). Further, for the wideband masker data, there was relatively more backward than forward masking in the youngest listeners tested, confirming the non-significant trends observed by Buss *et al.* (1999).

Pronounced non-simultaneous masking in children is often interpreted in terms of temporal resolution, but it has also been suggested that an interaction between poor efficiency and peripheral compression is responsible for this effect (Hartley and Moore, 2002; Hill *et al.*, 2004). For comparable thresholds in adult listeners, reduced efficiency and non-linear compression predicts proportionally greater forward *and* backward masking in young listeners. In particular, accounts based on age-dependent efficiency would not predict a reduction or a reversal in window asymmetry. As such, an account based on efficiency is inconsistent with the relative dominance of backward masking in the data for the younger children obtained with the wideband masker.

In the wideband masker data, the temporal window was characterized in terms of the ERD and asymmetry of the best-fitting temporal window. Both the ERD and asymmetry differed across age groups whether or not this model incorporated non-linear compression, suggesting that compression may not be critical to the age effects observed. An important caveat, however, is that the model did not produce higher estimates of criterion SNR at threshold for younger listeners. Previous studies of children have argued that efficiency is poorer in younger listeners in a number of behavioral tasks, including those using psychophysical (Hall and Grose, 1991a, 1994; Hartley and Moore, 2002; Hill *et al.*, 2004) and speech stimuli (Stuart *et al.*, 2006; Stuart, 2008). A failure to produce higher estimates of criterion for younger children in the present experiment could indicate a poor model fit. Because the signal used in the present study is brief, there is a trading relationship between the width of the window and the criterion at threshold. It is possible that relatively poor fits to the data resulted in inflated estimates of the ERD, which were compensated for by reduced estimates of criterion. This is unlikely to affect estimates of the temporal window asymmetry, however.

It is unclear how to account for age effects in temporal window asymmetry. It could be related to a bias for children to give more weight to information occurring late in the signal presentation (as in Hall *et al.*, 2007) or to maturation in the ability to identify the peak SNR at the output of the temporal window (Hartley *et al.*, 2000).

B. Effects of signal frequency

For the 1000-Hz signal, the MPP of children >6.5 yrs more closely resembled that of children <6.5 yrs than adults. At the 6500-Hz signal frequency, this pattern was reversed. While these signal-frequency effects were statistically significant for the ERD, they were not significant in the analyses of temporal window symmetry. These trends are qualitatively consistent with those of previous studies showing that the maturation of sensitivity at low-frequencies lags that observed at high frequencies. Trehub *et al.* (1988) reported that detection thresholds for bands of noise matured earlier at high than low frequencies. Whereas performance at 400 and 1000 Hz continued to improve up to 10 yrs of age, detection at 10 kHz was adult-like in 4 to 5 year-olds. In addition, there is some evidence that these frequency-specific developmental trends are most pronounced for brief signals. He *et al.* (2010) found that temporal integration in a tone detection task was adult-like when child listeners were tested at 6500 Hz but not when they were tested at 1625 Hz. Adult-like performance in children at high but not low frequencies is particularly interesting because it demonstrates that the central processing abilities of child listeners support reliable performance of the task. This implies that global factors, like a general inability to sustain attention, cannot account for the relatively poor performance at low frequencies. It is still unclear what frequency-specific factors are responsible for these age effects.

C. Effects of masker bandwidth

In adult data, thresholds for detecting a masked pure tone are higher than expected by the power spectrum model if the masker is a narrowband noise (Bos and de Boer, 1966). In a narrowband noise masker, thresholds for a brief signal do not depend on the timing relative to the inherent modulation of the masker: Thresholds are similar for a signal coincident with envelope minima and maxima (Buus *et al.*, 1996). Poor tone detection in a fluctuating narrowband masker is often attributed to perceptual similarities between the signal and features of the masker envelope. Increasing the masker bandwidth is thought to introduce off-frequency cues that indicate "when to listen" (Puleo and Pastore, 1980; Moore and Glasberg, 1982). This type of cuing may be related to comodulation masking release, wherein coherent masker envelope fluctuation remote from the signal frequency improves the ability to benefit from transient improvements in SNR (Hall and Grose, 1991b). Published data indicate that children can show larger effects of masker bandwidth than adults (Veloso *et al.*, 1990; Grose *et al.*, 1993). It has been suggested that stimulus fluctuation may challenge the central processing abilities of young listeners, resulting in age effects particularly for narrowband stimuli with pronounced inherent modulation (Grose *et al.*, 1993).

In the present study, both adults and children benefited more from the masker modulation for the wide masker than for the narrow masker. The range of the MPP increased with increasing noise bandwidth by 7 to 8 dB in both age groups.

The finding of comparable benefits of band widening across age groups was unexpected in light of the previous results of Grose *et al.* (1993). In that study, children were particularly poor at detecting a tone in a modulated narrow band of noise. This difference could be due to differences in signal duration. Whereas the present study used a brief signal with no steady state, Grose *et al.* (1993) employed 400-ms signal duration. It is possible that adults are better than children at making use of the change in envelope statistics associated with adding a long-duration pure-tone signal to a narrowband noise masker (e.g., reduction of envelope fluctuation). This possibility receives some support from data indicating that children are unable to use envelope cues available when a long-duration signal is added to a low-fluctuation noise sample (Buss *et al.*, 2006). Whereas children may be poor at making use of within-channel cues based on a change in envelope statistics, these cues may play little or no role in detection of a brief signal in a modulated narrowband noise.

D. Limitations of model fits

Estimates of the ERD and temporal window asymmetry differed across age groups in similar ways for models with and without non-linear compression. The quality of the fits was better in the linear model, however. Given that we know compression is acting at the level of the cochlea, it might be surprising that incorporating this transformation does not improve the data fits. There are at least two possible reasons why this was the case. First, it is possible that the transformation in Eq. (2) is not optimal for the conditions considered here. The exact nature of the compressive function in humans is the subject of on-going research (Wojtczak and Oxenham, 2009; Gregan *et al.*, 2011), and it is possible that modifying the function used here could provide a better data fit. A second factor to consider is that the shape of the window fitted in the present model may be more appropriate for a linear model than a non-linear model. Much of the early work using this function was based on a linear model (e.g., Moore *et al.*, 1988). It is possible that incorporating a different window function would improve the fits with a model incorporating compression. Regardless of these factors, a model incorporating instantaneous compression does not predict a developmental difference in temporal window asymmetry.

IV. SUMMARY

Results of these experiments are consistent with the following conclusions.

(1) Brief-tone thresholds were higher for young children than adults in both steady and amplitude-modulated masking noise.

(2) The ability to benefit from transient reductions in masker level was greater for maskers with wide than narrow bandwidths, despite the fact that all maskers were at least 1.4 ERBs wide. This effect was evident in the data of both adults and children.

(3) Young children were less able to benefit from the introduction of masker modulation minima than adults. That is, their MPPs tend to be shallower.

(4) For the wideband (21.3-ERB) masker, there was relatively more backward than forward masking in the youngest children compared to adults. This is consistent with a change in temporal window asymmetry over the course of development. Although some developmental effects of non-simultaneous masking are consistent with an interaction between compression and efficiency, such an interaction cannot account for the change in asymmetry observed here.

(5) Children 6.5 to 10 yrs of age were more adult-like in their ability to benefit from masker *AM* for a 6500-Hz signal than a 1000-Hz signal. This finding is consistent with earlier maturation of temporal processing at the higher signal frequency.

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[1] Most models assume that efficiency is a characteristic of the listener rather than the stimulus. For example, efficiency determines the SNR necessary for detection of a brief signal, with stability in that SNR over different stimulus conditions (e.g., over signal/masker delays in backward masking). It has also been suggested that efficiency could be affected by task or stimulus characteristics. For example, Hall and Grose (1994) proposed that children might be particularly inefficient at processing temporal features of modulated stimuli. It is also theoretically possible that efficiency could change as a function of time *within* a stimulus, although this would be very difficult to distinguish from other aspects of auditory processing, such as temporal resolution. The prediction that forward and backward masking should be comparably elevated in early development assumes that efficiency is fixed across stimulus conditions. A second caveat to this prediction is that non-simultaneous stimulus presentation does not rule out simultaneous masking at the level of the basilar membrane. At very short signal/masker delays, ringing and interactions at the level of the cochlea occur, particularly for forward masking (Duifhuis, 1973). Basilar membrane compression would be expected to have independent effects on signal and masker to the extent that transduction of these stimuli is temporally isolated.

[2] These nominal delays are rounded to the nearest integer. Actual delays were 57.5, 78.75, 100, 121.25, 142.5 and 200 ms. In conditions with the 5-ms ramps, the 57.5-ms delay was associated with a signal with an onset that began 5 ms after completion of the masker level reduction, and the 142.5-ms delay was associated with a signal offset that completed immediately before the subsequent masker level increase. For the 27.5-ms ramps, the signal and masker ramps temporally overlapped. The 100- and 200-ms delays were associated with signals that were temporally centered in the masker modulation minimum and maximum, respectively.

[3] For listeners with data in more than one sub-experiment the selection of data for each analysis was motivated solely by the goal of balancing the number of listeners in each group and signal frequency condition. Relatively few data points were omitted because most listeners who completed two sub-experiments provided data for one wide and one narrow masker, and analyses were performed separately for each masker bandwidth.

[4] Fits incorporating compression resulted in estimates of $Tp_b = 18.3$ and $Tp_a = 8.2$ for the adult data with the 6500-Hz signal and the wide masker. These values were fixed and the criterion was varied to generate the threshold estimates shown in Fig. 2.

ANSI (**2004**). ANSI S3.6-2004, *American National Standard Specification for Audiometers* (American National Standards Institute, New York).

Bos, C. E., and de Boer, E. (**1966**). "Masking and discrimination," J. Acoust. Soc. Am. **39**, 708–715.

Buss, E., Hall, J. W., and Grose, J. H. (**2006**). "Development and the role of internal noise in detection and discrimination thresholds with narrow band stimuli," J. Acoust. Soc. Am. **120**, 2777–2788.

Buss, E., Hall, J. W., Grose, J. H., and Dev, M. B. (**1999**). "Development of adult-like performance in backward, simultaneous, and forward masking," J. Speech Lang. Hear. Res. **42**, 844–849.

Buus, S., Zhang, L., and Florentine, M. (**1996**). "Stimulus-driven, time-varying weights for comodulation masking release," J. Acoust. Soc. Am. **99**, 2288–2297.

Duifhuis, H. (**1973**). "Consequences of peripheral frequency selectivity for nonsimultaneous masking," J. Acoust. Soc. Am. **54**, 1471–1488.

Eddins, D. A., and Green, D. M. (**1995**). "Temporal integration and temporal resolution," in *Hearing* (Academic Press, San Diego, CA), pp. 207–242.

Eddins, D. A., Hall, J. W., III, and Grose, J. H. (**1992**). "The detection of temporal gaps as a function of frequency region and absolute noise bandwidth," J. Acoust. Soc. Am. **91**, 1069–1077.

Festen, J. M., and Plomp, R. (**1981**). "Relations between auditory functions in normal hearing," J. Acoust. Soc. Am. **70**, 356–369.

Forrest, T. G., and Green, D. M. (**1987**). "Detection of partially filled gaps in noise and the temporal modulation transfer function," J. Acoust. Soc. Am. **82**, 1933–1943.

Glasberg, B. R., and Moore, B. C. J. (**1990**). "Derivation of auditory filter shapes from notched-noise data," Hear. Res. **47**, 103–138.

Gregan, M. J., Nelson, P. B., and, Oxenham, A. J. (**2011**). "Behavioral estimates of basilar-membrane compression: Additivity of forward masking in noise-masked normal-hearing listeners," J. Acoust. Soc. Am. **130**, 2835–2844.

Grose, J. H., Hall, J. W., and Gibbs, C. (**1993**). "Temporal analysis in children," J. Speech Hear. Res. **36**, 351–356.

Hall, J. W., Buss, E., and Grose, J. H. (**2007**). "The binaural temporal window in adults and children," J. Acoust. Soc. Am. **121**, 401–410.

Hall, J. W., and Grose, J. H. (**1991a**). "Notched-noise measures of frequency selectivity in adults and children using fixed-masker-level and fixed-signal-level presentation," J. Speech Hear. Res. **34**, 651–660.

Hall, J. W., and Grose, J. H. (**1991b**). "Relative contributions of envelope maxima and minima to comodulation masking release," Q. J. Exp. Psychol. A **43**, 349–372.

Hall, J. W., and Grose, J. H. (**1994**). "Development of temporal resolution in children as measured by the temporal modulation transfer function," J. Acoust. Soc. Am. **96**, 150–154.

Hall, J. W., Haggard, M. P., and Fernandes, M. A. (**1984**). "Detection in noise by spectro-temporal pattern analysis," J. Acoust. Soc. Am. **76**, 50–56.

Hartley, D. E., Wright, B. A., Hogan, S. C., and Moore, D. R. (**2000**). "Age-related improvements in auditory backward and simultaneous masking in 6- to 10-year-old children," J. Speech Lang. Hear. Res. **43**, 1402–1415.

Hartley, D. E. H., and Moore, D. R. (**2002**). "Auditory processing efficiency deficits in children with developmental language impairments," J. Acoust. Soc. Am. **112**, 2962–2966.

He, S., Buss, E., and Hall, J. W. (**2010**). "Monaural temporal integration and temporally selective listening in children and adults," J. Acoust. Soc. Am. **127**, 3643–3653.

Hill, P. R., Hartley, D. E., Glasberg, B. R., Moore, B. C., and Moore, D. R. (**2004**). "Auditory processing efficiency and temporal resolution in children and adults," J. Speech Lang. Hear. Res. **47**, 1022–1029.

Irwin, R. J., Ball, A. K., Kay, N., Stillman, J. A., and Rosser, J. (**1985**). "The development of auditory temporal acuity in children," Child Dev. **56**, 614–620.

Levitt, H. (**1971**). "Transformed up-down methods in psychoacoustics," J. Acoust. Soc. Am. **49**, 467–477.

Moore, B. C. J., and Glasberg, B. R. (**1982**). "Contralateral and ipsilateral cueing in forward masking," J. Acoust. Soc. Am. **71**, 942–945.

Moore, B. C. J., Glasberg, B. R., Plack, C. J., and Biswas, A. K. (**1988**). "The shape of the ear's temporal window," J. Acoust. Soc. Am. **83**, 1102–1116.

Oxenham, A. J., and Moore, B. C. (**1994**). "Modeling the additivity of nonsimultaneous masking," Hear. Res. **80**, 105–118.

Penner, M. J. (**1979**). "Forward masking with equal-energy maskers," J. Acoust. Soc. Am. **66**, 1719–1724.

Plack, C. J., and Moore, B. C. J. (**1990**). "Temporal window shape as a function of frequency and level," J. Acoust. Soc. Am. **87**, 2178–2187.

Puleo, J. S., and Pastore, R. E. (**1980**). "Contralateral cueing effects in backward masking," J. Acoust. Soc. Am. **67**, 947–951.

Stuart, A. (**2008**). "Reception thresholds for sentences in quiet, continuous noise, and interrupted noise in school-age children," J. Am. Acad. Audiol **19**, 135–146; quiz 191–132.

Stuart, A., Givens, G. D., Walker, L. J., and Elangovan, S. (**2006**). "Auditory temporal resolution in normal-hearing preschool children revealed by word recognition in continuous and interrupted noise," J. Acoust. Soc. Am. **119**, 1946–1949.

Trehub, S. E., Schneider, B. A., and Henderson, J. L. (**1995**). "Gap detection in infants, children, and adults," J. Acoust. Soc. Am. **98**, 2532–2541.

Trehub, S. E., Schneider, B. A., Morrongiello, B. A., and Thorpe, L. A. (**1988**). "Auditory sensitivity in school-age children," J. Exp. Child Psychol. **46**, 273–285.

Veloso, K., Hall, J. W., III, and Grose, J. H. (**1990**). "Frequency selectivity and comodulation masking release in adults and in 6-year-old children," J. Speech Hear. Res. **33**, 96–102.

Viemeister, N. F. (**1979**). "Temporal modulation transfer functions based upon modulation thresholds," J. Acoust. Soc. Am. **66**, 1364–1380.

Wightman, F., Allen, P., Dolan, T., Kistler, D., and Jamieson, D. (**1989**). "Temporal resolution in children," Child Dev. **60**, 611–624.

Wojtczak, M., and Oxenham, A. J. (**2009**). "Pitfalls in behavioral estimates of basilar-membrane compression in humans," J. Acoust. Soc. Am. **125**, 270–281.

Zera, J., and Green, D. M. (**1993**). "Detecting temporal asynchrony with asynchronous standards," J. Acoust. Soc. Am. **93**, 1571–1579.

Zwicker, E., and Schorn, K. (**1982**). "Temporal resolution in hard-of-hearing patients," Audiology **21**, 474–492.