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Masking by a Remote-Frequency Noise Band in Children and Adults

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INTRODUCTION

Adults detect tones at expected frequencies better than at unexpected frequencies (e.g., Dai et al. 1991). Infants, however, detect expected and unexpected frequencies equally well (Bargones & Werner 1994). Thus, adults listen selectively in the frequency domain, whereas infants appear to monitor a broad frequency range. One consequence of unselective listening in the frequency domain is that infants show masking in conditions associated with little masking for adults. Werner and Bargones (1991) demonstrated that infants are susceptible to remote-frequency or “distraction” masking, in that a 4–10 kHz noise can produce significant simultaneous masking of a 1-kHz signal. Thresholds for infants were about 10 dB higher in the remote-frequency noise than in quiet, regardless of whether masker level was 40 or 50 dB SPL. In contrast, thresholds for adults were similar in quiet and both levels of the noise. Changes in masking with masker level are consistent with energetic (peripheral) masking effects (e.g., Moore et al. 1997). Thus, these data suggest central effects.

This study examined whether remote-frequency noise masking extends into the school-aged years. It is generally assumed that children listen more selectively with increasing age, and should therefore be less susceptible to remote-frequency masking than infants, but remote-noise conditions have not been tested. Results from several studies suggest that selective auditory attention remains immature into at least the preschool years (e.g., Doyle 1973; Stellmack et al. 1997; Wightman & Kistler 2005). For example, five-year-olds had larger perceptual weights for intense distracting tones in selective-listening experiments than adults (Stellmack et al. 1997). Selective attending in the frequency domain likely continues to improve with age through childhood, but the time course is not clear.

MATERIALS AND METHODS

Listeners

Twenty-three children (4–9 years) and eight adults (19–33 years) participated. Two groups of children were tested: (1) eleven younger children aged 4–6 years and (2) twelve older children aged 7–9 years. Group average ages were 5.9 years ($SD = 0.6$) for younger children, 8.3 years ($SD = 0.9$) for older children, and 22.3 years ($SD = 4.5$) for adults. All listeners had normal hearing, with thresholds less than or equal to 25 dB HL for octave frequencies between 250 and 8000 Hz (ANSI 1996). Two additional children were tested

(4.1 and 4.6 years), but excluded from data analysis because they could not complete the conditions.

Stimuli and conditions

The signal was a 500-ms, 1-kHz tone, including 20-ms, $\cos^2$ ramps. The masker consisted of 50 different samples of bandpass noise with cutoff frequencies of 4 and 10 kHz, two octaves above the signal frequency. The masker samples were digitally generated in MATLAB. A 10 second buffer of the bandpass noise was created by applying a finite-impulse-response (FIR) filter to a Gaussian noise. The 500-ms noise samples (5-ms $\cos^2$ rise/fall) were drawn from this buffer with a random starting point within the longer buffer. The passband gain was 0.5 dB and the stop-band gain was -120 dB. One masker sample was selected without replacement for each presentation interval at an overall level of 40 or 60 dB SPL across conditions. For signal intervals, the selected masker sample was presented simultaneously with the signal (when present) for 500 ms.

Stimuli were digitally generated at a sampling rate of 22.05 kHz with a 24-bit resolution and output by a high-quality sound card with anti-aliasing circuitry and a dynamic range of 114 dB (CardDeluxe, Digital Audio Labs). The headphone output of the soundcard was presented monaurally to the listener's left ear via a Sennheiser HD-25 headphone. The headphone was calibrated by presenting a 1-kHz sinusoid through the headphone into an artificial ear coupler (Larson-Davis, AEC1010). The experiment was controlled by custom software.

Listeners were tested individually in a single-walled, sound-treated room. Octave band ambient noise measurements were taken with both the lights and ventilation fan turned on inside the sound-treated room and the building's air conditioning system operating fully. These "worst case" measurements were lower than the maximum permissible ambient noise levels for audiometric test rooms as specified by ANSI (1999) using supra-aural earphones for the octave band intervals ranging from 0.125 to 8 kHz.

Procedure

Children sat in front of a touch-screen monitor and listened to sounds presented via the earphones. An experimenter sat next to the child in the booth to initiate trials and enter responses. Adults were tested using the same procedure, but were alone in the booth and initiated trials and entered responses directly. Correct responses were rewarded by an engaging image presented on the monitor.

Thresholds for the 1-kHz signal were measured using a two-interval, forced-choice (2IFC) adaptive procedure that estimated 70.7% on the psychometric function (Levitt, 1971). Sessions began with a training phase, which ended when the listener correctly responded to five consecutive training trials that had a clearly audible signal. In the testing phase, starting level for the signal was 10–15 dB above expected threshold. An initial step size of 4 dB was decreased to 2 dB after the second reversal. Testing continued until 8 reversals were obtained and threshold was the average of the last six reversals. Listeners completed two blocks of trials for each condition, with condition order randomized. If the two threshold estimates differed by more than 5 dB, an additional block was completed, and the two estimates in best agreement were used. Individual data reported are averages across the two threshold estimates.

RESULTS

Average thresholds and amount of masking across listeners for each age group as well as individual thresholds are given in Table I. Quiet thresholds ranged from -0.5 to 17.5 dB

SPL (average = 7.2 dB SPL) for younger children, from -2.7 to 14.7 dB SPL (average = 2.5 dB SPL) for older children and from -6.8 to 14.7 dB SPL (average = 2.3 dB SPL) for adults. A one-way analysis of variance (ANOVA) indicated no significant difference in quiet threshold across the three age groups [$F(2,28)=2.3$; $p=0.1$], likely due to large individual differences within groups. That is, considerable between-subjects variability in absolute threshold was observed for all three age groups. For example, absolute thresholds spanned a range of 20, 17, and 22 dB for younger children, older children and adults, respectively. While previous investigations have reported a similar range of performance for school-aged children (e.g., Oh et al., 2001), the range of adult thresholds is larger than typically reported for adults.

Average amounts of masking (difference in threshold between the masker and quiet conditions) for the remote-frequency masker at 40 and 60 dB SPL are shown by the solid and patterned bars in Figure 1, respectively. For younger children, average threshold for the 1-kHz signal in the presence of the 40-dB SPL masker was 3.5 dB higher than their threshold for the same signal in quiet and 3.6 dB higher for the 60-dB SPL masker condition. No systematic evidence of masking was observed for the two masker conditions for older children or for adults.

A repeated-measures ANOVA with Masker Level as a within-subjects factor and Age as a between-subjects factor was performed on amount of masking. The main effect of Masker Level was not significant [$F(1,28)=0.9$, $p=0.8$], indicating similar masked thresholds across masker level. Moreover, thresholds for the 40-dB masker condition accounted for 92% of the variance in thresholds for the 60-dB masker condition. The ANOVA confirmed a significant main effect of Age [$F(2,28)=5.3$, $p<0.05$], indicating developmental effects in susceptibility to remote-noise masking. *Post hoc* pairwise comparisons (Bonferroni, using a criterion of $p<0.05$) indicated significantly greater masking for younger children than for older children or adults. Amount of remote-noise masking was not significantly different across older children and adults, and the Masker Level $\times$ Age interaction was not significant [$F(2,28)=4.0$, $p=0.2$].

Remote-noise masking was not observed for all 4–6 year-old children, as shown in Table I. Whereas six younger children showed masking effects of 3 dB or greater for both masker levels, five younger children showed little or no remote-frequency masking. Two older children (OC11 and OC12), but none of the adults, showed a masking effect of 3 dB or greater.

DISCUSSION

The main result of this study is that average threshold was elevated by a significant amount for the 4–6 year-old group in the presence of the remote-frequency noise relative to quiet. In contrast, no systematic masking effects were observed for the 7–9 year-old or adult groups. Because frequency resolution is believed to be mature by about six months of age (see Werner 2007), and because thresholds did not change when masker level was increased by 20 dB, younger children's susceptibility to masking by a remote-frequency noise is not likely due to an immature sensory representation of the signal and masker. Instead, this susceptibility appears to reflect developmental changes in central auditory processes such as a reduced ability to selectively attend to the signal frequency.

This study was based on Werner and Bargones (1991), who found an average masking effect of 10 dB for six-month-olds using similar stimuli. Consistent with the infant results, the remote-frequency noise increased thresholds for 4–6 year-olds in the current study. However, the average masking effect of 3.5 dB for 4–6 year-olds here was smaller than the

10-dB effect reported for the infants. Differences in methodology might contribute to this discrepancy. Listeners in the current study were tested with a 2IFC procedure, whereas Werner and Bargones (1991) used a single-interval, observer-based procedure. Alternatively, the smaller effect observed for 4–6 year-olds may reflect an age-related improvement in the ability to selectively attend to the signal frequency and ignore the noise. Consistent with this idea, five (out of a total of 11) of the 4–6 year-olds did not show masking effects. In contrast, nearly all infants tested by Werner and Bargones (1991) were susceptible to remote-noise masking.

One unanswered question is the degree to which these findings generalize to natural listening environments. Children are more susceptible to masking than adults for both nonspeech and speech sounds (e.g., Nittrouer & Boothroyd 1990; Wightman et al. 2003). Moreover, preschoolers and kindergarteners are often more susceptible to interference from complex sounds than older, school-aged children (e.g., Wightman et al. 2003; Leibold & Neff, 2007). These findings suggest that children require years of listening experience to learn to focus on the most informative aspects of complex sounds such as speech in the presence of competing background sounds.

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Figure 1.

Average amount of masking (difference in threshold between masked and quiet conditions) for 4–6 year-olds, 7–9 year-olds and adults in the presence of remote-frequency noise at 40 dB SPL (solid bars) or 60 dB SPL (hatched bars). Error bars represent +1 SE. Data falling at or below the dotted horizontal line indicate no masking.

TABLE I

Thresholds in dB SPL and amount of masking in dB for individual younger children (4–6 years), older children (7–9 years) and adults for the 1-kHz pure-tone signal in quiet and in the presence of the remote-frequency noise masker. In separate conditions, the overall level of the masker was 40 or 60 dB SPL. The age of each listener is given in years.

LISTENER (Age in Years)	THRESHOLDS (dB SPL)		AMOUNT OF MASKING (Masked-Quiet Threshold in dB)		
	Quiet	40 dB SPL Masker	60 dB SPL Masker	40 dB SPL Masker	60 dB SPL Masker
		Younger Children (4–6 years)			
YC1 (4.9)	13.5	21.8	23.2	8.3	9.7
YC2 (5.3)	14.2	18.0	12.5	3.8	–1.7
YC3 (5.4)	–0.5	4.0	6.5	4.5	7
YC4 (5.5)	7.4	12.3	14.2	4.9	6.8
YC5 (5.5)	8.0	11.7	15.2	3.7	7.2
YC6 (5.6)	9.3	10.2	8.3	0.9	–1
YC7 (5.9)	5.5	7.0	6.7	1.5	1.2
YC8 (6.4)	2.2	2.8	2.7	0.6	0.5
YC9 (6.5)	–2.2	–2.5	–1.8	–0.3	0.4
YC10 (6.6)	3.8	7.3	8.0	3.5	4.2
YC11 (6.7)	17.5	25.2	23.3	7.7	5.8
Mean	7.2	10.7	10.8	3.5	3.6
SE	1.9	2.5	2.5	0.8	1.2
		Older Children (7–9 years)			
OC1 (7.1)	4.1	3.3	3.8	–0.8	–0.3
OC2 (7.1)	3.7	5.8	6.2	2.1	2.5
OC3 (7.2)	0.3	2.7	4.0	2.4	3.7
OC4 (7.8)	14.7	15.0	14.0	0.3	–0.7
OC5 (8.0)	1.7	–0.5	–3.3	–2.2	–5
OC6 (8.0)	5.7	–4.0	–0.3	–9.7	–6
OC7 (8.2)	–1.0	–0.8	–0.8	0.2	0.2
OC8 (8.2)	–2.7	–2.8	–3.3	–0.1	–0.6
OC9 (9.3)	0.8	1.2	2.5	0.4	1.7
OC10 (9.3)	–1.3	–6.8	–2.5	–5.5	–1.2

LISTENER (Age in Years)	THRESHOLDS (dB SPL)			AMOUNT OF MASKING (Masked-Quiet Threshold in dB)		
	Quiet	40 dB SPL Masker	60 dB SPL Masker	40 dB SPL Masker	60 dB SPL Masker	60 dB SPL Masker
OC11 (9.3)	-1.3	2.0	4.2	3.3		5.5
OC12 (9.8)	5.7	10.8	9.7	5.1		4
Mean	2.5	2.2	2.8	-0.4		0.3
SE	1.4	1.8	1.5	1.2		1.0
Adults						
A1	14.7	16.7	11.8	2		-2.9
A2	1.5	-1.7	-0.3	-3.2		-1.8
A3	-3.0	-2.3	-5.0	0.7		-2
A4	-6.8	-4.7	-8.7	2.1		-1.9
A5	9.0	9.5	7.8	0.5		-1.2
A6	0.8	3.0	4.5	2.2		3.7
A7	-0.7	-0.5	0.0	0.2		0.7
A8	3.2	0.7	1.3	-2.5		-1.9
Mean	2.3	2.6	1.4	0.3		-0.9
SE	2.4	2.5	2.3	0.7		0.8