Research Article

Cues for Diotic and Dichotic Detection of a 500-Hz Tone in Noise Vary with Hearing Loss

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ABSTRACT

Hearing in noise is a challenge for all listeners, especially for those with hearing loss. This study compares cues used for detection of a low-frequency tone in noise by older listeners with and without hearing loss to those of younger listeners with normal hearing. Performance varies significantly across different reproducible, or “frozen,” masker waveforms. Analysis of these waveforms allows identification of the cues that are used for detection. This study included diotic (N_0S_0) and dichotic (N_0S_π) detection of a 500-Hz tone, with either narrowband or wideband masker waveforms. Both diotic and dichotic detection patterns (hit and false alarm rates) across the ensembles of noise maskers were predicted by envelope-slope cues, and diotic results were also predicted by energy cues. The relative importance of energy and envelope cues for diotic detection was explored with a roving-level paradigm that made energy cues unreliable. Most older listeners with normal hearing or mild hearing loss depended on envelope-related temporal cues, even for this low-frequency target. As hearing threshold at 500 Hz increased, the cues for diotic detection transitioned from envelope to energy cues. Diotic detection patterns for young listeners with normal hearing are best predicted by a model that combines temporal- and energy-related cues; in contrast, combining cues did not improve predictions for older listeners with or without

hearing loss. Dichotic detection results for all groups of listeners were best predicted by interaural envelope cues, which significantly outperformed the classic cues based on interaural time and level differences or their optimal combination.

Keywords: masked detection, sensorineural hearing loss

INTRODUCTION

The challenge of detecting and identifying sounds in background noise is not only a classic problem in psychophysics but also a practical issue for listeners with or without hearing loss. A better understanding of this problem could be useful for developing assistive devices for communication in background noise. Previous studies have identified cues and strategies for detecting tones in reproducible noise (Pfafflin and Mathews 1966; Gilkey et al. 1985; Zwicker and Henning 1985; Isabelle and Colburn 1987, 1991; Davidson et al. 2006, 2009a, b; Mao et al. 2013; Mao and Carney 2014, 2015). These studies collected detailed patterns of hits and false alarms for an ensemble of reproducible noise waveforms. These detection patterns were analyzed to test hypotheses that various acoustic cues, or their combinations, could predict the detection results. These studies focused on young listeners with normal hearing (Y_{NH}). In the current study, this approach was extended to older listeners with normal hearing (O_{NH}) or mild or moderate sensorineural hearing loss (O_{HL}).

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Early studies of detection in noise typically used maskers that were generated independently for each trial (Blodgett et al. 1958, 1962; Dolan and Robinson 1967). A number of models have been proposed to explain thresholds for diotic (same noise and tone presented to both ears, N_0S_0) and dichotic (same noise to both ears, but inverted tone to one ear, N_0S_π) detection and the difference between these thresholds, referred to as the binaural masking level difference (BMLD) (Hirsh 1948). Later studies used ensembles of reproducible masker waveforms that were digitally generated and stored, for repeated use over several sessions (Gilkey et al. 1985; Isabelle and Colburn 1991; Evilsizer et al. 2002; Davidson et al. 2006, 2009a). These studies reveal that some noise waveforms are significantly more effective maskers of a 500-Hz tone than others, across listeners and over time. Studies using reproducible noise maskers allow detailed analysis of the masker waveform features, or cues, to explain patterns of hits and false alarms. Energy cues generally explain a portion of the variance in the detection patterns. Energy cues may be based on a critical band (CB) model (Fletcher 1940) for the frequency channel centered on the target tone frequency, or on the multiple detector (MD) model, which compares energy across frequency channels (Gilkey and Robinson 1986). Temporal cues, based on either the fine structure or envelope, can also explain a portion of the variance in detection patterns (Isabelle and Colburn 1991; Davidson et al. 2009a, b). The similarity between detection patterns, or the underlying acoustic cues, has not previously been studied in listeners with sensorineural hearing loss (SNHL).

A series of recent studies modeled detection of a 500-Hz tone in reproducible noise by Y_{NH} listeners using combinations of acoustic cues. Responses for both narrowband and wideband maskers were examined. Diotic wideband and narrowband detection patterns are best described by a model that optimally combines critical band energy, envelope, and temporal fine structure cues (Mao et al. 2013). Dichotic wideband detection patterns are best explained by a model based on the slope of interaural envelope differences (SIED, Mao and Carney 2014, 2015), which substantially outperformed models based on classic interaural time (ITD) and level (ILD) cues, or an optimal combination of these cues, for the wideband condition (Mao and Carney 2014, 2015). The SIED is a nonlinear combination of ITD and ILD (Mao and Carney 2014). Dichotic narrowband detection patterns vary more across listeners than for the other stimulus conditions studied (Isabelle 1995; Evilsizer et al. 2002; Davidson et al. 2009b). Individual and combined ITD and ILD cues were not successful in explaining the dichotic narrowband

detection patterns. SIED cues were more successful than ITD and/or ILD, and SIED cues derived from envelope differences of interaural channels tuned to mismatched frequencies could often explain more variance in the narrowband dichotic results, with the best frequency-channel combinations varying among listeners (Mao and Carney 2014, 2015).

The current study was designed to test the hypothesis that older listeners with or without mild to moderate SNHL use the same cues and strategies for detecting tones in noise as Y_{NH} listeners. The same narrowband and wideband reproducible noise waveforms were used as in previous studies (Evilsizer et al. 2002; Davidson et al. 2006; Mao and Carney 2014), and models based on several acoustic features and their combinations were used to explain the variation in performance across masker waveforms. In addition, a roving-level task (Gilkey 1987; Green 1988; Kidd et al. 1989; Henning et al. 2005) was used for the diotic condition to test the relative contributions of envelope and energy cues for individual listeners.

METHODS

Listeners

Results are presented for 19 listeners with hearing thresholds ranging from normal to moderate hearing loss, illustrated by the average thresholds in Figure 1 and Table 1. Eight listeners were older controls (ages 53–79) with normal hearing (O_{NH}); these listeners had pure tone average thresholds (PTA, averaged across 0.5, 1, and 2 kHz) of less than 20 dB hearing level (HL). Six listeners (ages 62–85) had mild (M) hearing loss (PTA between 20 and 40 dB HL), and five listeners (ages 68–88) had moderate (MD) hearing loss (PTA between 40 and 60 dB HL). All listeners had symmetric hearing loss (<15 dB difference in HL up to 4 kHz). Bone conduction thresholds

FIG. 1. Average audiograms for the listeners tested in this study. Older listeners with normal hearing (O_{NH}) and listeners with mild or moderate sensorineural hearing loss, based on PTAs for 0.5, 1, and 2 kHz.

TABLE 1

Hearing status and tone-in-noise thresholds for older subjects, categorized as normal (O_{NH}), mild (M), or moderate (MD) based on the PTA

Subject	Age (years)	Hearing status			Wideband thresholds and BMLD			Narrowband thresholds and BMLD		
		HL type	500-Hz (dB HL)	PTA (dB HL)	N_0S_0 (dB SPL)	N_0S_π (dB SPL)	BMLD (dB)	N_0S_0 (dB SPL)	N_0S_π (dB SPL)	BMLD (dB)
S43	79	O_{NH}	2.5	5.8	15.9	3.17	12.7	13.0	4.17	8.8
S36	64	O_{NH}	5.0	16.6	12.4	1.17	11.2	14.7	2.17	12.5
S24	66	O_{NH}	7.5	5.8	12.4	3.57	8.8	13.9	NF	–
S32	76	O_{NH}	7.5	11.6	16.0	13.1	2.9	15.6	INC	–
S64	71	O_{NH}	7.5	12.5	14.2	3.57	10.6	16.1	NF	–
S69	53	O_{NH}	7.5	5.0	14.6	1.07	13.5	12.8	0.67	12.1
S21	78	O_{NH}	10.0	18.3	13.6	6.07	7.5	12.8	3.47	9.3
S68	62	M	10.0	20.0	13.4	–0.03	13.4	13.2	NF	–
S35	75	O_{NH}	17.5	19.1	14.1	12.4	1.7	14.2	13.6	0.6
S53	85	M	17.5	36.6	13.4	10.7	2.7	12.9	8.87	4.0
S63	63	M	20.0	27.5	13.2	0.87	12.3	14.1	6.27	7.8
S40	68	MD	25.0	40.8	12.3	0.67	11.6	9.87	0.27	9.6
S66	62	M	27.5	35.0	12.3	4.37	7.9	11.6	4.57	7.0
S60	70	M	35.0	30.8	13.7	9.57	4.1	15.5	NF	–
S23	88	MD	35.0	41.6	14.5	11.6	2.9	14.0	12.0	2.0
S50	78	M	37.5	35.0	13.7	10.2	3.5	12.6	9.37	3.2
S51	81	MD	37.5	45.0	17.6	18.1	–0.5	15.2	15.1	0.1
S70	77	MD	45.0	44.1	22.3	16.6	5.7	12.8	11.8	1.0
S61	77	MD	47.5	42.5	20.2	18.9	1.3	17.0	16.0	1.0

Subjects are listed in order of hearing threshold at 500 Hz (dB HL). Thresholds for tone-in-noise detection are in signal-to-noise energy (dB), reported used $E_{SNR} = L - N + 10 \log_{10}(D/1 \text{ s})$, where L is the tone level in dB SPL, N is the noise spectrum level (40 dB SPL), and D is the duration in seconds (0.3 s) (Evilsizer et al. 2002). Noise levels were 40 dB SPL spectrum level for both bandwidths (overall noise levels were 60 and 75 dB SPL RMS for narrowband and wideband conditions, respectively). Stimulus duration was 0.3 s. Four subjects (NF) did not finish testing the last condition (N_0S_π NB); one subject had relatively inconsistent detection patterns for N_0S_π NB (INC). All other detection patterns were statistically significant (χ^2 test, 24 *df*, $p < 0.001$)

were consistent with a sensorineural hearing loss. The results for the listeners in this study were compared to those of ten young listeners with normal hearing (Y_{NH}) from previous studies that used the same sets of reproducible masker waveforms (Evilsizer et al. 2002; Davidson et al. 2006; Mao and Carney 2014).

Stimuli and Test Procedures

Four stimulus conditions were tested: N_0S_0 and N_0S_π binaural conditions were each tested using wideband and narrowband maskers. Reproducible maskers were randomly selected on each trial from an ensemble of 25 tokens of band-limited white wideband (100–3000 Hz) noise or white narrowband (452–552 Hz, approximately one critical band, geometrically centered at 500 Hz). The narrowband noise spectra were extracted from the wideband spectra, so that the two sets of 25 maskers had identical spectra surrounding the 500-Hz target tone. Noises were always presented diotically (N_0) at 40 dB SPL spectrum level, corresponding to levels of approximately 60 and 75 dB SPL for the narrowband and wideband maskers, respectively. The 500-Hz tone targets were presented in phase to the two ears for the N_0S_0 condition, or 180° out of phase for the N_0S_π condition. Each trial contained a single stimulus interval, with a 50 % chance of a target tone added to the masker waveform. Tone levels were varied using a

two-down, one-up (2D1U) paradigm (Levitt 1971). Tones and maskers were 300 ms in duration and were gated simultaneously using 10-ms raised-cosine ramps.

The hit and false alarm rates for the ensemble masker waveforms in each stimulus condition are referred to as detection patterns (Fig. 2A) (Davidson et al. 2006). A detection pattern was estimated for each stimulus condition before moving on to the next condition; wideband testing preceded narrowband, and diotic testing preceded dichotic testing for each bandwidth. Each test block was a single 2D1U track, 100 trials in duration. Each track included two presentations of each of the 25 maskers alone and two presentations of each of the 25 maskers with an added target tone. Within each track, over the course of ten trials, five were randomly selected to be noise-alone trials and five were tone-plus-noise trials; each set of ten trials had a different random sequence. This strategy avoided long runs of either trial type.

The initial tone level in each track was started at approximately 10 dB above the listener's threshold for that condition, based on initial test results. Because the tests involved a single-interval task, bias was closely monitored. Bias was computed using $\beta = -0.5 (Z_H + Z_{FA})$, where Z_H and Z_{FA} were the z scores for hit and false alarm rates, respectively. Blocks that were biased toward either “tone present” or “noise-alone” responses, as indicated by absolute values of β greater

FIG. 2. **A** Average detection patterns for hits (*left*) and false alarms (*right*) for the wideband N_0S_0 condition for Y_{NH} listeners (based on data from ten listeners, combined across Evliss et al. 2002; Davidson et al. 2006; Mao and Carney 2014). **B** Example hit and FA detection patterns for the same condition for one older listener (S63) with mild SNHL.

than 0.3, were discarded. The number of test blocks in each condition varied depending upon both the bias and the stability of each listener's results. Each block required approximately 5–7 min, and 5–12 blocks were completed in each 1-h session. An average of 35 blocks was completed per condition, ranging from 25 to 132 blocks, depending upon each subject's bias and the stability of their results (see below).

Analysis

For each stimulus condition, the threshold for each track was estimated by averaging an even number of reversals, after omitting the first four reversals. Then, an average threshold across tracks was computed. All tone-plus-noise trials that were within ± 2 dB of the overall average threshold, plus noise-alone trials that occurred between these tone-plus-noise trials, were included in the further analysis of detection patterns. This strategy allowed testing using a relatively straightforward tracking paradigm, while collecting many trials near threshold (approximately $d' = 1$) for analysis of detection patterns. Detection patterns were constructed by compiling the hit rate (correct detections) and false alarm (FA) rate for each masker waveform. Detection patterns for Y_{NH} tested with the tracking paradigm were highly correlated to patterns collected using fixed-level stimuli in previous studies (Mao and Carney 2014).

Consistency of the detection patterns was tested in two ways: first, a χ^2 statistic was computed to test the hypothesis that the detection pattern was statistically different from that expected for draws from a

binomial distribution (Siegel and Colburn 1989); second, the Pearson product-moment correlation of the z scores of the detection patterns for the first-half and last-half of each listener's trials was used to test the consistency of a detection pattern across the data set, which sometimes spanned several sessions. Testing in each condition continued until at least 25 trials within ± 2 dB of the mean threshold were collected for each stimulus waveform (i.e., for both the masker-alone waveform and for the tone-plus-masker waveform). The consistency of detection patterns was assessed using a χ^2 analysis. If detection patterns were not consistent based on the initial data, testing continued until consistency was observed, if possible. One listener's detection patterns for the N_0S_π NB condition were inconsistent and were not included in further analyses, and four listeners (two O_{NH} and two with moderate loss) did not complete this final test condition (see Table 1).

To determine the cues that were used by listeners for the detection task, predictions of the detection patterns were made using decision variables (DVs) based on energy, envelope, and fine structure cues for diotic conditions (Mao et al. 2013) and on interaural cues for the dichotic conditions (Mao and Carney 2014). The CB cue (Fletcher 1940) was computed as the root-mean-squared value (RMS) of the output of a 4th-order gammatone filter centered at 500 Hz. The diotic envelope-slope (ES) cue (Richards 1992; Zhang 2004; Davidson et al. 2006; Mao et al. 2013) was also computed based on the response of the 500-Hz gammatone filter. A modulation filter centered at 120 Hz, with $Q=1$, was applied to the envelope before

computing the average of the absolute value of the slope over the time course of the waveform. The band-pass modulation filter emphasized the part of the modulation spectrum that has the most salient cues indicating presence of the 500-Hz tone (Mao et al. 2013). The fine structure cue was computed using the phase opponency (PO) model (Carney et al. 2002; Davidson et al. 2006, 2009b), which is based on the correlation of two auditory nerve (AN) models with characteristic frequencies (CFs) that straddle the target tone. The response of the PO model has been shown in past studies to be correlated to detection patterns for detection of a 500-Hz tone in noise (Carney et al. 2002; Davidson et al. 2006, 2009b; Mao et al. 2013). Other strategies for computing fine structure cues, such as synchrony to the 500-Hz tone, do not vary as much from masker to masker and are not significantly correlated to listeners' detection patterns. The CFs of the model fibers differ by approximately one equivalent rectangular bandwidth and are approximately 180° out of phase at the target frequency of 500 Hz. Thus, the presence of a tone at 500 Hz reduces the correlation between the two model fibers; this cross-correlation, similar to the response of a coincidence detector, was used as the DV for the fine structure cue. For listeners with hearing loss, this fine structure prediction was made in two ways: with the normal AN model and with an AN model impaired to match the listener's hearing loss at 500 Hz (Zilany et al. 2009, 2014). In the latter case, the difference between the two model CFs was increased to maintain the 180° phase difference at 500 Hz.

The decision criterion for each DV was determined by computing distributions of values for 200 random noises with the same statistics as the masker waveforms, with and without tones added at each listener's threshold level. In addition to predictions of diotic detection patterns based on these three single cues, predictions were made using an optimal combination of the cues, weighted by their cross-covariance, in a likelihood ratio test (Mao et al. 2013). The quality of the predictions was evaluated based on the percentage of the variance in the detection patterns that was explained by each cue or combination of cues.

The energy and envelope-slope cues for diotic detection are highly correlated, but these two cues can be teased apart using the roving-level paradigm (Green 1988; Kidd et al. 1989; Dai and Kidd 2009). Randomly varying the overall level, on a trial-to-trial basis, makes the energy cue unreliable but does not affect the normalized envelope-slope cue. For these tests, the same single-interval 2D1U paradigm was used to find the threshold signal-to-noise ratio; however, before each trial, a level was drawn from a 20-dB uniform distribution (± 10 dB centered around

the fixed-level stimuli); both tone and noise were amplified or attenuated by the value selected for that trial. The threshold SNR was computed for these blocks, as above, and detection patterns were constructed from trials within ± 2 dB of the estimated threshold. Thresholds were directly compared between roving and nonroving conditions. Increases in threshold of approximately 25 % of the rove range, 5 dB in this case, were interpreted as evidence that the listeners were using energy-related cues (Green 1988). The Pearson product-moment correlation was computed between the detection patterns estimated for each condition to determine whether the roving-level paradigm had a significant effect on these patterns.

Dichotic detection patterns were predicted using ITD, ILD, and SIED cues, as in Mao and Carney (2014). DVs were the variance of ITD or ILD and the average of the absolute value of the slope of the interaural envelope difference. These cues were computed from the responses of gammatone filters to the waveforms presented to each ear, with tone levels at each listener's threshold. Although the target tone was always at 500 Hz, the potential role of channels tuned to other frequencies was explored. The percentage of the variance explained by various interaural combinations of frequency channels was examined. For ITD and ILD cues, the results shown are based on the 500-Hz filters for both ears; results for other frequency channels were not significantly better than these predictions. For the SIED cue, especially in the narrowband condition, better predictions were often provided by interaural combinations of gammatone filters centered at other frequencies. For the narrowband condition, the percent of the variance that could be explained was displayed for various interaural frequency combinations.

RESULTS

Table 1 provides thresholds for a 500-Hz tone in quiet (reported as dB HL) and for the 500-Hz tone in noise for both wideband and narrowband conditions (reported as energy signal-to-noise ratio, E_{SNR} , dB). Four listeners did not complete the narrowband N_0S_0 condition, which was the final testing condition, and one was not able to provide consistent results in that testing condition. For those listeners, detection patterns for the other three stimulus conditions were still analyzed.

Examples of average detection patterns for hits and FAs for Y_{NH} listeners (N_0S_0 WB condition) are shown in Figure 2A. These patterns are characterized by large differences in the hit and FA rates across

different noise waveforms. The general similarity between this pattern and one example of a listener with mild hearing loss (selected from the middle of Table 1) can be seen by comparing A and B of Figure 2. The differences between the O_{NH} and O_{HL} listeners' patterns and the average Y_{NH} patterns were analyzed, as well as the ability of different cues to explain these patterns for each listener. Average detection patterns for Y_{NH} listeners were compared to the older listeners' patterns for both wideband conditions and for the N_0S_0 narrowband condition. For the N_0S_π narrowband condition, Y_{NH} detection patterns vary significantly across listeners (Mao and Carney 2014), so a representative average pattern is not available for this condition.

Differences across listeners in the cues or strategies used for detecting tones in noise should result in differences in their detection patterns. Therefore, a first analysis of these results was to determine whether there were significant changes in the detection patterns, in comparison to the Y_{NH} patterns, as a function of hearing threshold, age, or masked threshold. Trends in the similarity of the detection patterns were evaluated using the coefficient of determination (r^2), examined as a function of age, threshold at 500 Hz, PTA, and tone-in-noise thresholds. Highly statistically significant trends in the percentage of common variance in the older and younger listeners' hit detection patterns were found as a function of HL at 500 Hz (Fig. 3A) and of 500-Hz tone-in-noise thresholds (Fig. 3B). The trends in similarity of hits as a function of PTA were more weakly, but significantly, correlated ($p < 0.03$) (not shown). Trends in the similarity of FA patterns were significantly correlated to masked thresholds for both N_0S_0 and N_0S_π wideband conditions ($p < 0.001$), but not for the N_0S_0 narrowband condition (not shown). Trends in the similarity of FA patterns were not significantly correlated to HL at 500 Hz, or PTA. Trends in similarity of detection patterns were not significantly correlated to age for either hits or FAs (not shown). The results in Figure 3 show that detection patterns in older listeners differ from those of Y_{NH} listeners and that the difference increases with hearing loss. The next phase of the analysis was to examine the cues used by each listener for the detection task and to determine whether these cues changed with hearing loss.

Cues for Diotic Detection

Predictions of the variance in the diotic detection patterns for the wideband (Fig. 4) and narrowband (Fig. 5) conditions were made for individual and optimally combined cues (as in Mao et al. 2013). The amount of variance in the detection patterns that was predicted is plotted as a function of hearing threshold

FIG. 3. Common variance between each of the O_{NH} and O_{HL} detection patterns for hits and the average Y_{NH} detection pattern, plotted as a function of **A** hearing threshold at 500 Hz (dB HL) and **B** tone-in-noise threshold (E_{SNR} , dB) for N_0S_0 wideband (left panel), N_0S_0 narrowband (center panel), and N_0S_π wideband (right panel) maskers. The common variance between each pair of patterns is based on the coefficient of determination, or the square of the Pearson product-moment correlation between the z scores for the detection patterns being compared. The solid line is the linear regression fit to the data; r^2 and p values are shown for each fit. Y_{NH} detection patterns for the narrowband N_0S_π condition vary considerably across listeners; therefore, a representative average Y_{NH} pattern is not available for this condition (see Mao and Carney 2014).

at 500 Hz in dB HL; results for the average Y_{NH} listener are shown at the left of each plot. Comparisons of the predictions made by different cues were evaluated using t tests on the correlation values for three groups of listeners; groups were based on hearing threshold at 500 Hz (HL <15, 15–30, and >30 dB). Average correlations for each group are shown in Table 2. In general, energy and envelope-slope cues predicted significantly more variance in the detection patterns than fine structure cues predicted (for each group comparison $p < 0.02$). Also, significantly more of the variance in the results was predicted for hits than for FAs based on the CB and ENV cues ($p < 0.001$ for both comparisons), but there was no significant difference for the PO cue ($p = 0.2$). These general results are consistent with earlier studies that applied these models to average Y_{NH} listeners (e.g., Davidson et al. 2006, 2009a, b; Mao et al. 2013). For the older listeners, several trends are apparent in the results as a function of hearing threshold.

FIG. 4. Proportion of predicted variance in the wideband diotic detection patterns for each of the older listeners and for the average Y_{NH} listener (*left*). Results are plotted along the ordinate according to the hearing threshold at 500 Hz, averaged across the two ears (see Table 1). *Bold lines on the abscissa* indicate a single hearing threshold that is applied to

more than one listener; *symbols* are separated along the abscissa for clarity. The *horizontal dotted line* indicates statistical significance for the proportion of predicted variance. Trends in the predictions based on each cue are highlighted by *lines* that were computed using a local linear regression.

Predictions based on temporal fine structure, made using the PO model, predicted a statistically significant amount of variance for listeners with less than

approximately 20 dB HL (Figs. 4 and 5). In the wideband condition (Fig. 4), the fine structure cue did not provide significant predictions of the detec-

FIG. 5. Proportion of predicted variance in the narrowband diotic detection patterns for each of the older listeners and for the average Y_{NH} listener (*left*). Results are plotted along the ordinate according to hearing threshold 500 Hz, averaged across the two ears (see Table 1). Format same as Figure 4.

TABLE 2

Average correlations between predictions and diotic hit and FA detection patterns for each cue, for three groups of listeners based on hearing threshold at 500 Hz. Values with magnitude greater than 0.4 are significant. Results for individual listeners are plotted in Figures 4 and 5 as amounts of predicted variance (r^2)

Subject group (HL)	CB	ENV	PO	Comb
Wideband hits				
<15 dB ($n=8$)	0.734	-0.693	-0.570	0.736
15–30 dB ($n=5$)	0.685	-0.638	-0.276	0.684
>30 dB ($n=6$)	0.639	-0.482	0.022	0.635
Wideband FAs				
<15 dB ($n=8$)	0.430	-0.400	-0.454	0.393
15–30 dB ($n=5$)	0.602	-0.484	-0.314	0.531
>30 dB ($n=6$)	0.310	-0.141	0.088	0.153
Narrowband hits				
<15 dB ($n=8$)	0.677	-0.745	-0.514	0.734
15–30 dB ($n=5$)	0.766	-0.622	-0.190	0.786
>30 dB ($n=6$)	0.738	-0.351	0.088	0.730
Narrowband FAs				
<15 dB ($n=8$)	0.336	-0.488	-0.493	0.3915
15–30 dB ($n=5$)	0.656	-0.390	-0.221	0.468
>30 dB ($n=6$)	0.633	-0.166	-0.334	0.256

tion patterns for any listeners with hearing thresholds greater than 18 dB HL. Predictions based on the fine structure cue were made in two ways: using an auditory nerve model for an ear with normal hearing and using models that had elevated thresholds matched to each listener's hearing threshold at 500 Hz. Hearing loss was introduced by varying both inner and outer hair cell coefficients in the auditory nerve model (Zilany and Bruce 2006, 2007). Results shown in Figures 4 and 5 are for the model with simulated hearing loss; however, there were no significant differences in the results for the two modeling approaches.

The CB cue predicted significantly more of the variance in listeners' results as compared to the PO cue for both wideband and narrowband conditions ($p < 0.01$), and in the wideband condition, predictions based on the ENV cue were also significantly greater than for the PO cue ($p < 0.01$). For listeners with hearing thresholds at 500 Hz greater than approximately 20 dB HL (wideband, Fig. 4) or 10 dB HL (narrowband, Fig. 5), the CB and ENV cues predicted similar amounts of variance. However, for the two groups of listeners with hearing thresholds greater than 15 dB HL at 500 Hz, the energy cue predicted significantly more of the variance in the detection patterns (Figs. 4 and 5; $p < 0.01$). For the two listeners with the most hearing

loss at 500 Hz, predictions based on CB and ENV cues were similar for the wideband condition. The relative importance of energy and envelope-slope cues was further examined with the roving-level paradigm described below, which makes the energy cue unreliable.

For the average Y_{NH} listener, the best predictions of variance in detection patterns are provided by a model that optimally combines the energy, envelope-slope, and temporal fine structure cues (Mao et al. 2013). For the older listeners, even those with normal hearing, there were no listeners for whom combined cues explained significantly more variance than the best single cue, even for individuals for whom the fine structure cue provided statistically significant predictions.

The energy and envelope-slope cues are significantly correlated (Mao et al. 2013). Thus, a roving-level paradigm was used to further examine the relative importance of these cues in masked detection for a subset of the individual listeners. Because the roving-level paradigm makes the energy cue unreliable (Gilkey 1987; Green 1988; Kidd et al. 1989), its effect on thresholds in a detection task reveals whether or not listeners are depending upon energy cues. Elevation of detection thresholds by approximately 25 % of the rove range, or 5 dB in this case, was interpreted as evidence for the dependence of a listener on energy cues in the fixed-level condition (Green 1988). In this experiment, it was also possible to compare detection patterns for the roving-level task to those for the fixed-level task. Thus, a detailed examination of whether or not the roving-level paradigm affected performance was possible.

For two O_{NH} listeners (S43, S36) and one listener with mild loss (S40), the roving-level paradigm did not affect detection thresholds (i.e., threshold differences were < 5 dB, Fig. 6A, B) and the detection patterns for fixed and roving-level conditions were strongly correlated (Fig. 6C, D; $r > 0.4$ indicates a significant correlation), in either the narrowband or wideband conditions. For some listeners with mild hearing loss and for those with more hearing loss, the roving-level paradigm elevated thresholds by approximately 5 dB, suggesting that these listeners were using energy cues to do the task. The correlations between fixed and roving-level detection patterns for these listeners were reduced but still significant in the wideband condition and dropped below significance in the narrowband condition (see below). The effect was observed more often in the narrowband condition (Fig. 6B, D). In general, the results for the roving-level paradigm were consistent with the results shown in Figures 4 and 5, that is, when the energy cue predicted a substantially greater amount of variance in the fixed-level condi-

FIG. 6. Comparisons of fixed- and roving-level thresholds (*top: A, B*) and detection patterns (*bottom: C, D*). *Top:* Thresholds for fixed- (*blue*) and roving-level (*red*) paradigms for wideband (*left*) and narrowband (*right*) diotic conditions. *Bottom:* Pearson product-moment correlation coefficient between fixed- and roving-level detection patterns for hits (*green*) and FAs (*yellow*). *Double dagger:*

S35's narrowband detection pattern in the roving-level paradigm did not reach the criterion for consistency. *Single dagger:* the correlations between S70's and S61's fixed-level and roving-level narrowband detection patterns were not statistically significant; all other correlations were significant ($p < 0.05$).

tion as compared to the envelope-slope cue, the listeners were more affected by the roving-level paradigm. Two listeners (S35, S66) were recruited for the roving-level task because the energy and envelope-slope cues predicted similar amounts of variance in their wideband results, but the energy cue predicted much more variance than the envelope cue in the narrowband condition. As expected, these listeners' thresholds and detection patterns were not affected by the roving-level paradigm in the wideband condition but were greatly affected in the narrowband condition (S35, S66 in Fig. 6). The results for these listeners, as well as the differences in amounts of variance predicted by the energy and envelope-slope cues between bandwidths for several listeners with hearing thresholds of 10–20 dB HL (Figs. 4 and 5), make it clear that an individual listener may use different cues for masked detection in different listening conditions. The listener with the highest thresholds at 500 Hz had tone-in-noise detection thresholds and detection patterns that were elevated by approximately 5 dB in the roving-level paradigm for both bandwidths (S60, Fig. 6).

In general, the listeners whose thresholds were elevated by the roving-level paradigm reported great difficulty performing the roving-level task in the affected condition, and their detection patterns were far less consistent than for the fixed-level testing. Listeners for whom thresholds were not affected did not report difficulty in the roving-level condition, and detection pattern consistency was similar to that for fixed-level testing. One additional listener (S50) had an increased threshold in the wideband roving-level condition, but was not able to perform the roving-

level task consistently enough to estimate detection patterns (not shown).

Cues for Dichotic Detection

Predictions of detection patterns for dichotic detection were made using the classic binaural cues, variance of ITD and ILD (Isabelle and Colburn 1987, 1991), as well as SIED (Mao and Carney 2014, 2015). Figure 7 shows the amount of variance for both wideband and narrowband detection patterns. The interaural cues are only present for trials with the out-of-phase tone added to the noise; therefore, only hit detection patterns are analyzed here. In general, the ITD and ILD cues did not predict a significant amount of the variance in the wideband detection patterns for the older listeners, with or without hearing loss, although these cues predicted small but significant amounts of variance for Y_{NH} subjects (Mao and Carney 2014). In the narrowband condition, predictions of variance in the detection patterns made with the ITD cue reached statistical significance for many subjects, though ILD cues did not make significant predictions. Note that there is no “average” Y_{NH} listener in the narrowband condition; correlations of detection patterns across subjects are not strong enough to establish an average pattern that applies across listeners in the dichotic narrowband condition (Evilsizer et al. 2002; Isabelle and Colburn 1987, 1991). Note that a few listeners did not complete the dichotic narrowband condition, which was tested last, or did not achieve stable detection patterns in this condition (see Table 1).

FIG. 7. Proportion of variance in dichotic detection patterns of hits for wideband and narrowband conditions. Same format as Figure 4.

SIED cues were computed in two ways: the standard SIED cue was based on interaural envelope differences between the 500-Hz frequency channels from the two ears, and the best SIED cue was based on the combination of interaural frequencies that predicted the most variance in the dichotic detection patterns (Fig. 7). These predictions varied smoothly as a function of interaural frequency (Figs. 8 and 9), and the amount of variance predicted by the best SIED cue in Figure 7 was based on the global maximum across all frequency combinations tested. As above, comparisons between predictions made by different cues were based on t tests of the correlations for three groups of listeners; groups were based on hearing threshold at 500 Hz (HL <15, 15–30, and >30 dB). Average correlations for each group are listed in Table 3.

For the wideband condition, predictions based on the standard SIED cue were significantly better than those based on ITD and ILD for both groups of listeners with hearing thresholds less than 30 dB ($p < 0.01$ for both comparisons for both groups). As for the ENV cue in the wideband diotic condition (Figs. 4 and 5), the envelope-based SIED cue predicted less of the variance in the detection patterns for listeners with the highest hearing thresholds at 500 Hz. The SIED predictions were not significantly greater than ITD and ILD predictions for this group, and for many of these listeners, none of these predictions were significant (Fig. 7, top). In the narrowband dichotic condition, predictions based on the standard SIED, ITD, and ILD cues were weak, often not reaching significance (Fig. 7, bottom). For

all three groups of listeners and both narrowband and wideband conditions, the best SIED cue significantly outperformed the standard SIED cue ($p < 0.04$ for all three groups and both conditions). The frequency pairs that provided the best SIED predictions varied across listeners, but for individual listeners, a systematic pattern was often observed. The diversity of patterns is illustrated by the examples in Figures 8 and 9. In the wideband dichotic condition (Fig. 8), the variance in detection patterns for all Y_{NH} listeners was best predicted by interaural envelope differences between frequency channels tuned close to 500 Hz (Mao and Carney 2014); this pattern was observed for some O_{NH} listeners (e.g., S43, Fig. 8, upper left). In contrast, the interaural frequency combinations that provided the best wideband predictions varied across O_{HL} listeners (Fig. 8). In the narrowband dichotic condition, Y_{NH} , O_{NH} , and O_{HL} listeners all apparently had diverse strategies, reflected in the low correlations between detection patterns for different listeners, although each listener had self-consistent detection patterns. The diversity of frequency combinations that provided the best predictions of the narrowband dichotic detection patterns is illustrated in Figure 9 for four listeners with a range of hearing thresholds at 500 Hz. The patterns in Figures 8 and 9 can be partly understood in terms of the dominance of one ear or the effective use of both ears (i.e., monaural or binaural listening). In listeners for whom binaural cues dominated, the patterns were “diagonal,” with a particular combination of frequency channels providing the best predictions (e.g., S43, S66). In the wideband condition, this pattern was often offset from

FIG. 8. Predicted variance in wideband N_0S_π detection patterns for four listeners with a range of hearing thresholds at 500 Hz. Each pixel represents a single combination of frequency channels from the two ears. The best SIED prediction shown in Figure 7 was selected from this range of frequency combinations. The

gray scale for the percent of variance accounted for is the same for all panels. Contour lines surround values that are significant at the $p < 0.01$ level ($r^2 > 0.254$).

FIG. 9. Predicted variance in narrowband N_0S_π detection patterns for four listeners with a range of hearing thresholds at 500 Hz. Same format as Figure 8. Contour lines surround values that are significant at the $p < 0.01$ level ($r^2 > 0.254$).

TABLE 3

Average correlations between predictions and dichotic hit and FA detection patterns for each cue, for three groups of listeners based on hearing threshold at 500 Hz. Values with magnitude greater than 0.4 are significant. Results for individual listeners are plotted in Figure 7 as amounts of predicted variance (r^2)

Subject group (HL)	ILD	ITD	SIED standard	SIED best
Wideband hits				
<15 dB ($n=8$)	0.150	0.164	-0.546	-0.678
15–30 dB ($n=5$)	0.325	0.182	-0.456	-0.725
>30 dB ($n=6$)	0.047	0.055	-0.268	-0.575
Narrowband hits				
<15 dB ($n=4$)	-0.212	-0.309	-0.1384	-0.713
15–30 dB ($n=5$)	-0.224	-0.437	-0.403	-0.757
>30 dB ($n=5$)	0.034	-0.399	-0.300	-0.706

500 Hz (e.g., S66), and the offset differed across subjects. For a given subject, the wideband and narrowband frequency combinations that provided the best predictions often differed (cf. S43, S66, Figs. 8 and 9). In listeners for which one ear dominated, the patterns in Figures 8 and 9 were horizontal (S35) or vertical (S70), that is, the best predictions were based on a small range of frequencies in one ear or the other; S35's detection patterns were best predicted by frequencies near 500 Hz, whereas S70's were best predicted by channels closer to 550 Hz.

The patterns in Figures 8 and 9 can be further interpreted in terms of the ability of energy cues to predict the detection patterns. For example, for three listeners (S35, S70, S61), approximately 60 % of the variance in the narrowband dichotic detection patterns was described by the energy in the CB at 500 Hz computed for one ear. These listeners had very small BMLDs (Table 1); apparently, they did not make effective use of binaural cues for the detection task. Because their N_0S_π thresholds were similar to their N_0S_0 thresholds, the stimuli in the dichotic condition had substantial energy cues. For each of these listeners, the dominant ear had a hearing threshold 10–15 dB lower than the opposite ear at 500 Hz. CB energy explained the detection pattern for only one of these listeners (S35) in the wideband dichotic condition. For this listener, the pattern of frequency pairs that provided significant predictions for both bandwidths (Figs. 8 and 9, S35) was horizontal, reflecting the dominance of the right ear. For two other listeners with 10 dB differences in hearing threshold at 500 Hz (S21 and S40), small but significant amounts of variance were predicted by CB energy in the dominant ear. Both of these listeners had relatively large BMLDs, consistent with

the inability of energy cues to explain a large amount of the variance in their results.

DISCUSSION

This study examined cues used for detection of a low-frequency (500 Hz) tone in noise for older listeners with normal hearing or mild to moderate SNHL. In contrast to previous studies that have explored the use of fine structure and envelope cues by attempting to eliminate or reduce one or the other cue (e.g., Shannon et al. 1995; Lorenzi et al. 2006; Hopkins and Moore 2010), both of these temporal cues, plus energy cues, were always present in the tone detection task used here. The simultaneous presence of these three cues is typical for natural stimuli. A strength of the reproducible noise method is that it allows the quantification of each cue's influence on detection while using stimuli in which all cues are present. The detection patterns for both O_{NH} and O_{HL} listeners differed significantly from average Y_{NH} patterns (Fig. 3) and, thus, provided a window into changes in the cues used for masked detection across a range of listeners. Whereas Y_{NH} listeners apparently combine energy and both fine structure and envelope cues (Mao et al. 2013), the temporal fine structure cues predicted little or no variance in either diotic or dichotic detection results for O_{NH} and O_{HL} listeners (Figs. 4, 5, and 7). Energy and envelope-slope cues were both found to predict significant amounts of variance in diotic detection patterns for O_{NH} and O_{HL} listeners. These two cues are also strongly correlated to each other across waveforms; therefore, a roving-level task (Green 1988; Kidd et al. 1989; Henning et al. 2005) was used to evaluate the relative importance of energy and envelope-slope cues. Randomly varying the sound level from interval to interval renders the energy cue unreliable, without affecting normalized envelope-slope cues (Richards 1992; Zhang 2004). The roving-level paradigm does not significantly affect detection thresholds in Y_{NH} listeners for these bandwidths and durations (Gilkey 1987; Kidd et al. 1989; Henning et al. 2005). Here, neither threshold nor detection patterns were affected by the roving-level paradigm for O_{NH} listeners or for O_{HL} listeners with mild SNHL, suggesting that envelope-related cues dominated the diotic results for these listeners (Fig. 6). Thresholds and detection patterns for listeners with greater hearing thresholds and with detection patterns that were best explained by energy cues (Figs. 4 and 5) were most affected by the roving-level paradigm, consistent with the conclusion that these listeners depended upon energy rather than envelope-based cues. A key finding of the

current study was that, in general, as the hearing threshold at 500 Hz increases, listeners rely less on envelope cues and more on energy cues.

The diotic results here are generally consistent with other studies that have suggested that listeners with SNHL make less use of temporal fine structure cues than do Y_{NH} listeners. For example, the results here are consistent with the findings of Henry and Heinz (2012), which showed a reduction in auditory nerve phase-locking in ears with SNHL in the presence of noise. Several studies of fine structure and envelope cues in listeners with SNHL have focused on intelligibility of vocoded speech (e.g., Apoux and Bacon 2004; Lorenzi et al. 2006; Hopkins and Moore 2010; Fogerty and Humes 2012) and have found that the utility of temporal fine structure cues are reduced by SNHL. Additionally, studies with temporally jittered and/or spectrally smeared stimuli suggest that the use of fine structure cues is diminished in older listeners (Pichora-Fuller et al. 2007; MacDonald et al. 2010). Consistent with these results, the present study showed that temporal fine structure cues were not able to explain significant variance in detection patterns for a low-frequency tone in an ensemble of reproducible noises. However, a general finding here was that for stimuli in which all cues were present and undistorted, the role of temporal fine structure, for both diotic and dichotic masked detection, was relatively small, even for Y_{NH} and O_{NH} listeners, as compared to envelope- and energy-based cues. Fogerty and Humes (2012) also found that temporal fine structure cues were less important than envelope cues for speech intelligibility for stimuli in which both cues were present.

In general, the importance of envelope cues in predicting detection patterns decreased as hearing threshold increased at the target frequency of 500 Hz (Figs. 4 and 5). However, close examination of the results showed that in some cases the role of envelope cues varied considerably across subjects with similar hearing thresholds (e.g., compare subjects with hearing thresholds of 25–27.5 dB HL in Fig. 5). These results are consistent with the varied descriptions of amplitude-modulation sensitivity in listeners with SNHL (e.g., Bacon and Viemeister 1985; Formby 1987; Grant et al. 1998; Bacon and Gleitman 1992; Moore et al. 1992; Lorenzi et al. 2006). Physiological recordings of auditory nerve fibers in animals with noise-induced hearing loss have increased precision of temporal envelope coding (Kale and Heinz 2010; Henry et al. 2014). However, the results presented here did not suggest that envelope cues were more dominant in a tone-in-noise detection task for listeners with mild SNHL than for Y_{NH} listeners (Figs. 4 and 5), and with increased hearing loss, energy cues tended to be more dominant in the detection results.

In general, the differences in the roles of the cues examined here across subjects are generally consistent with the variability in masked thresholds reported for listeners with SNHL (e.g., Horwitz et al. 2012).

In addition to comparing the roles of the two temporal cues, which have been the focus of several previous studies, the relative role of energy cues was examined here. Results for diotic detection in the roving-level paradigm suggest that older listeners with normal hearing or mild SNHL, similar to Y_{NH} listeners, are not dependent on energy cues for detection in noise, but rather depend on a rove-resistant cue, such as envelope-slope (Richards 1992). Energy cues tended to dominate diotic detection for listeners with higher hearing thresholds at 500 Hz.

Dichotic detection results for O_{NH} listeners and O_{HL} listeners with mild SNHL were generally similar to those for Y_{NH} listeners, in that the SIED cue predicted significantly more variance in the wideband detection patterns than either ITD or ILD cues (Mao and Carney 2014, 2015). For the wideband condition, results for both Y_{NH} and O_{NH} listeners were best predicted by envelope differences across interaural channels tuned near the 500-Hz target frequency (Fig. 8). Results for O_{HL} listeners were often better predicted by mismatched combinations of frequency channels, which varied from subject to subject. For the narrowband condition, detection patterns for all groups of listeners were best predicted by mismatched combinations of interaural frequency channels, which varied across listeners (Mao and Carney 2014, 2015; Fig. 9). This finding is consistent with the general lack of consistency of dichotic narrowband detection patterns across Y_{NH} subjects in previous studies of dichotic detection in reproducible noises (e.g., Evilsizer et al. 2002; Isabelle and Colburn 1991) and suggests that different listeners adopt different strategies for the narrowband condition.

A dichotic roving-level task was not attempted with the single-interval task used for these reproducible noise studies. However, Henning et al. (2005) showed that in Y_{NH} listeners, a large (40 dB) interaural rove of stimulus level did not appreciably affect thresholds in a two-interval dichotic detection task (except for very short duration stimuli). Their results cannot be explained by either an ILD or an interaural envelope-energy cue, but a normalized interaural envelope cue, such as the SIED, could potentially explain robust performance in a roving-level dichotic task. Additionally, the duration dependence that they reported is consistent with a role for envelope-related cues, which require longer time intervals to be established, as compared to interaural level or time differences.

One interpretation of the results presented here is that Y_{NH} subjects are able to use a combination of

three redundant cues for the masked detection task: energy, envelope, and fine structure cues. O_{NH} and O_{HL} listeners with mild SNHL are able to use energy and envelope cues, but not fine structure cues, and thus, there is slightly less redundancy in the cues that they can use. Finally, O_{HL} listeners with higher thresholds at 500 Hz who depend primarily on energy cues would not benefit from any redundancy across cues. This lack of redundancy would be particularly detrimental for detection in background noise, which directly distorts energy cues.

The results presented here have implications for the design of signal-processing strategies. In general, algorithms should focus on the cues that can be, and are, used by individual listeners, and these cues vary with both aging and hearing loss (Pichora-Fuller and MacDonald 2008). In particular, Y_{NH} and O_{NH} listeners and O_{HL} listeners with mild SNHL depend primarily upon envelope-based cues for both diotic and dichotic detection in noise. Thus, a promising direction for developing and improving noise-robust signal-processing strategies for these listeners is to focus on restoring envelope cues. In the normal ear, envelope cues are translated into strong fluctuations in the time-varying discharge rate in the responses of AN fibers. Central neurons, particularly at the level of the inferior colliculus and higher, are tuned to fluctuations in the range that are enhanced by peripheral filtering, that is, best modulation frequencies of midbrain neurons are typically in the range of the bandwidths of peripheral filters at low frequencies. Therefore, envelope cues are particularly valuable for detection of low-frequency signals in background noise (Mao et al. 2013). In the normal ear, the *contrast* in fluctuations across frequency channels is further enhanced by peripheral nonlinearities such as saturation and synchrony capture. Envelope-related neural cues would be distorted by broadened peripheral filters, and the contrast in these cues across channels would be decreased by the reduced nonlinearities in the impaired ear. Signal-processing strategies to restore the contrast in envelope-related cues across frequency channels is feasible (Rao and Carney 2014).

The O_{HL} listeners in this study with moderate SNHL depended more upon energy-related cues for diotic detection. For these listeners, assistive signal-processing strategies should differ qualitatively from those developed for listeners who depend on envelope-based cues. Further studies are required to determine whether the dominance of energy vs. envelope-based cues vary within individual listeners across frequency. Such information would potentially allow the design of signal-processing schemes that are tailored to the cues used by individual listeners across different frequency ranges.

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