Individual and level-dependent differences in masking for adults with normal and impaired hearing

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Abstract: Simultaneous, on-frequency masking is commonly assumed to be linear with increasing noise intensity. However, some evidence suggests that, expressed in terms of signal-to-noise ratio changes with background level changes, masking slopes can vary from 0 dB/dB. These results and evidence from a large sample of subjects with normal and impaired hearing demonstrate level-dependent changes in masking, large individual differences in masking among subjects with similar thresholds in quiet, and significant correlations of masking slope with other estimates of auditory function measured in the same backgrounds.

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PACS numbers: 43.66.Dc, 43.66.Sr [QJF]

Date Received: December 27, 2011 **Date Accepted:** February 21, 2012

1. Introduction

As discussed by Houtsma (2004), results reported by Hawkins and Stevens (1950) are frequently cited to assert that simultaneous, on-frequency masking is generally linear with increasing noise intensity. That is, as the level of a broadband masker increases, masked detection thresholds increase by the same amount, resulting in a fixed signal-to-noise ratio (SNR) needed for threshold. Thus, expressed in terms of SNR changes with background level changes, linear masking slopes are 0 dB/dB. However, results from Houtsma (2004) are not consistent with this assertion, showing masking slopes >0 dB/dB, at least for broadband maskers with spectrum levels (N_0) in the range of 20 to 60 dB. A linear regression on the results for higher frequency signals yielded an average slope of 0.12 dB/dB. In an earlier comparison with data from Hawkins and Stevens (1950), Reed and Bilger (1973) also showed a deviation from linear masking slopes in simultaneous, on-frequency masking and a dependence of masking slope on masker spectrum level.

Individual differences in slopes of simultaneous, on-frequency masking have also been reported, even among younger adults with normal hearing (e.g., Dubno *et al.*, 2005). For 1000-Hz pure-tone signals in broadband speech-spectrum-shaped noise with overall rms levels from 70 to 84 dB SPL, masking slopes for nine subjects ranged from -0.12 to 0.43 dB/dB, with a mean of 0.17 dB/dB. In addition to pure-tone thresholds, word recognition was measured with the same levels of background noise. When audibility-based predictions of word recognition were estimated only from speech and noise spectra and did not take into account individual subjects' masked thresholds, observed scores decreased significantly relative to predicted scores as levels increased. However, when individual masked thresholds were used to represent the "effective" noise spectra, differences between observed and predicted scores remained constant as levels increased. That is, including individual differences in masking slopes significantly improved the accuracy of predictions for recognition of speech in noise, providing evidence that individual differences in masking slopes can explain individual

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differences in speech recognition in noise at different levels. Indeed, a significant negative correlation ($p < 0.05$) was observed at the highest speech and noise levels between slopes of word-recognition scores and weighted-average masked thresholds across frequency (computed using weights from the frequency importance function for the test words). That is, subjects whose word-recognition scores improved more with increases in speech level had shallower masking slopes.

Individual differences in the ability to detect gaps in noise markers in a steady-state background noise may also relate to individual differences in masking, if a given background noise level is effectively higher for some subjects than for others. Horwitz *et al.* (2011) reported thresholds for detection of gaps in noise markers at fixed marker-to-background ratios for a range of background noise levels. This gap detection experiment was designed and interpreted in terms of expected level-dependent changes in cochlear compression. Although not reported in Horwitz *et al.* (2011), the experimental design called for masked detection thresholds for the noise markers to be measured over the same range of broadband noise levels as gap detection. These masked thresholds and masking slopes are relevant to the question of individual and level-dependent differences in simultaneous, on-frequency masking and are included in this letter and compared to slopes for gap detection published in Horwitz *et al.* (2011).

2. Methods

2.1 Subjects

As reported in Horwitz *et al.* (2011), 38 right-handed subjects participated, spanning a wide range of hearing thresholds. Participants were organized into three groups based on their quiet thresholds, defined as the average detection threshold for two noise markers (1000-Hz-wide, presented here, and 50-Hz-wide, not included here) used in the original gap detection study. The three groups are as follows: Low Threshold group (mean age=35.8 yr, $n=18$, 13 females), Mid Threshold group (mean age=56.8 yr, $n=12$, 8 females), and High Threshold group (mean age=74.5 yr, $n=8$, 6 females). See Horwitz *et al.* (2011) for more details, including mean audiograms for the three subject groups. See also supplementary material.¹

2.2 Stimuli and apparatus

Detection in quiet and in background noise was measured for the 1000-Hz-wide signal centered at 1000 Hz, 400 ms in duration including 30-ms raised cosine rise and fall ramps. The 1000-Hz-wide signal was a low-fluctuation noise created with a custom-designed algorithm to produce an envelope with minimal dips and peaks. A 2000-Hz-wide low-fluctuation background noise was centered at 1020 Hz and recorded onto a CD for later playback. The same signals (with a temporal gap in the 1000-Hz signal) were used for the gap-detection measures in Horwitz *et al.* (2011).

Subjects were seated inside a double-walled sound-attenuating booth and registered responses via a button box (TDT RBOX). The signals were digitally generated with custom LABVIEW software (LABVIEW 8.5, National Instruments) and converted to analog using a 16-bit digital-to-analog converter (National Instruments, model 6052E) with a sampling rate of 50 kHz. The generated signals were low-pass filtered at 20 kHz (TDT FT5) and attenuated (TDT PA4). The signals were mixed (TDT SM3) with the background noise (Sony CDR-W66) and passed through a headphone buffer (TDT HB5) for presentation to the right ear through a TDH-39 (Telephonics) headphone.

2.3 Procedures

Detection thresholds for the background noise and for the signal with and without background noise were estimated using a three-alternative forced-choice (3AFC) adaptive procedure, which converged on the 70.7% point on the psychometric function. Following training to familiarize subjects with the task, the final threshold was the mean of two or three estimates. Signal levels are the rms level (dB SPL) within the equivalent

rectangular bandwidth (ERB) of an auditory filter centered around 1000 Hz (Glasberg and Moore, 1990)² to provide an estimate of signal energy within a critical band. Background levels are in spectrum level (dB) for comparison with previous experiments. Thresholds obtained during training were discarded, as were thresholds collected during the first runs in each subsequent day of data collection.

3. Results and discussion

Data were initially examined from 25 Low and Mid Threshold subjects for whom masked thresholds were obtained at identical background SPLs (spectrum levels of 0 to 24 dB, corresponding to 21 to 45 dB SPL). Results from these Low Threshold and Mid Threshold subjects provided a straightforward way to assess level-dependent changes in masking. The complete set of data, including results from the High Threshold subjects, was difficult to analyze because of the wider range of background noise levels used for the High Threshold subjects, as a result of their wider range of quiet thresholds. Background noise levels differed for each High Threshold subject and ranged from spectrum levels of 9 to 54 dB, in contrast to 0 to 24 dB for 25 of the Low and Mid Threshold subjects. For all subjects, background and masker levels were at least 5 dB above detection threshold for the background to minimize near-threshold effects.

Figure 1(a) shows mean detection thresholds in the broadband background noise at each background level, expressed as S/N_0 levels as a function of N_0 (following Fig. 4 in Houtsma, 2004). Plotted this way, if masking was linear, thresholds would fall on a horizontal line (i.e., a slope of 0 dB/dB). However, a systematic increase in masking with increases in background level is apparent, especially at the higher background levels. To quantify these level-dependent changes, masking slopes were obtained from separate linear regression functions for the lower and higher background levels (i.e., for background spectrum levels from 0 to 12 dB and from 12 to 24 dB). These mean linear regression functions are included in Fig. 1(a). For 18 of 25 subjects, masking slope is steeper for higher than lower levels (mean slopes: 0.13 dB/dB and 0.04 dB/dB, respectively), with a significant difference between mean slopes for the two levels [$t(24)=-2.31$; $p=0.03$]. Despite differences in signals and backgrounds,

Fig. 1. S/N_0 thresholds (dB) for 25 subjects plotted against background N_0 values from 0 to 24 dB. Lines show linear regression functions for background N_0 values from 0 to 12 dB and from 12 to 24 dB and are included in both panels: (a) mean (± 1 SEM) and (b) individual data for subjects in the Low Threshold (squares) and Mid Threshold (triangles) groups. A 28-dB S/N_0 threshold for one Mid Threshold subject in a background N_0 of 24 dB was omitted for clarity.

the current results are generally comparable to those from the 6 normal-hearing subjects in [Gregan *et al.* \(2010\)](#), in which mean masking slopes for a 4000-Hz signal in a broadband threshold-equalizing noise were 0.29 dB/dB and 0.01 dB/dB for background spectrum levels from ~ 14 to 24 dB and from -6 to 4 dB, respectively [$t(5)=-3.50$; $p=0.017$].

Sizable individual differences in masking can be seen in Fig. 1(b), which shows individual thresholds and the mean linear regression functions from Fig. 1(a). [Dubno and Schaefer \(1991\)](#) also reported large individual differences in masking, shown as critical ratios (their Fig. 4), even for subjects with similar quiet thresholds listening at fixed background noise levels. Another property of the current data (not shown in Fig. 1) is the consistency of individual differences in masking. Despite individual and level-dependent differences in masking, subjects with more masking at any given background level generally have more masking at other background levels. Indeed, comparing masking at the lowest, middle, and highest levels of background noise, significant correlations were obtained (correlation coefficients of 0.57, 0.66, and 0.57 and corresponding p values of 0.002, <0.001 , and 0.002, for correlations between the lowest and middle, lowest and highest, and middle and highest levels, respectively). Despite sizable variability in masked thresholds within and across these 25 subjects, the current results support previous findings of systematic increases in simultaneous, on-frequency masking with increasing background level, with larger increases as background spectrum level increases from 12 to 24 dB compared to increases from 0 to 12 dB. Finally, in addition to differences in masked thresholds across subjects, there are also substantial differences in masking slopes across subjects. As shown along the abscissa of Fig. 2, the range of masking slopes can be seen more fully in the complete set of data from all 38 subjects (including subjects from the High Threshold group).

Given the wide range of background noise levels used for the 38 subjects, masking slopes for each subject were obtained from a single linear regression function that included all background levels, rather than separate functions for the lower and higher background levels. Although the mean slope was 0.05 dB/dB, slopes for individuals ranged from -0.30 to 0.22 dB/dB and revealed large individual differences in level-dependent changes in masking.

As described in [Horwitz *et al.* \(2011\)](#), gap-detection slopes were obtained from a linear regression on all measured thresholds for the detection of gaps in the same 1000-Hz-wide signal at the same background levels as described earlier for detection

Fig. 2. Slopes of gap-detection thresholds with increasing background noise level (10 log ms/dB) plotted against masking slopes (dB/dB) for 38 subjects in the Low Threshold (squares), Mid Threshold (triangles), and High Threshold (circles) groups. The open circles represent the cases with the shallowest and steepest masking slopes.

thresholds. Detection of the 1000-Hz-wide signal in the broadband background noise and detection of a gap in the 1000-Hz-wide signal in the same background noise both likely reflect individual differences in masking. Indeed, slopes for gap detection and masking were significantly correlated ($r=0.77$, $p<0.001$). Figure 2 shows this correlation, with individual subjects' gap-detection slopes plotted against masking slopes. Subjects with more steeply positive masking slopes have more steeply positive gap-detection slopes, or gap detection that worsens more as background levels increase, consistent with both measures being influenced by a common mechanism related to level-dependent masking. Notably, subjects' quiet thresholds do not appear to be the underlying factor, as data overlap for subjects in the Low, Mid, and High Threshold groups. In fact, the most extreme data points (open circles) are from two subjects in the High Threshold group, suggesting that masking slopes may provide useful information to differentiate among subjects with similar magnitudes of hearing loss. Further, excluding the two High Threshold subjects with the lowest and highest slope values does not change the significance of the correlation between gap-detection and masking slopes ($r=0.67$, $p<0.001$), suggesting that this relationship is not simply driven by two outliers.

One possible explanation is that both slopes reflect level-dependent changes in cochlear nonlinearities, including changes in the effective bandwidth of the auditory filter. Specifically, auditory filters that broaden with increases in stimulus level would result in increasing noise power within the filter and increasing masking. This has been offered as at least a partial explanation for similar results for normal-hearing subjects showing positive simultaneous, on-frequency masking slopes, which have been reported for signal frequencies of 1000 Hz and higher (Oxenham *et al.*, 1997; Houtsma, 2004; Gregan *et al.*, 2010). Examples of shallower-than-normal slopes in some hearing-impaired subjects have also been reported (e.g., Nelson and Schroder, 1997; Baker and Rosen, 2002). Whereas there is general consensus that the normal effective auditory filter bandwidth increases as level increases, the limited data available for hearing-impaired subjects are more variable. Consistent with our variable, and often negative, masking slopes for subjects with higher thresholds, Baker and Rosen's data show a masking slope <0 dB/dB for a hearing-impaired subject for whom the estimated auditory filter bandwidth also decreased with increasing level. A recent study by Badri *et al.* (2011) reported increasingly wider auditory filter bandwidths with increases in level for subjects with normal thresholds yet poorer speech recognition in noise at unfavorable SNRs. These results also suggest that simultaneous masking slopes may provide a useful index to correlate with understanding of speech in increasing levels of noise.

More broadly, the data from the full set of 38 subjects, as well as from previous experiments reviewed here, suggest that level-dependent masking appears to reflect differences in auditory processing across subjects with similar pure-tone thresholds. Changes in auditory filter bandwidth may provide a partial explanation, but other non-linear effects, such as level-dependent changes in suppression and the medial olivocochlear reflex could also influence masking slopes. These same underlying factors likely combine to influence the processing and understanding of speech in noise. Speech communication involves listening to broadband signals in the presence of other broadband signals, the levels of which often change over time. Thus, given individual differences in masking slopes among subjects with similar quiet thresholds, further investigation may be warranted to determine if measures of simultaneous masking may help account for some of the variability in auditory function among hearing-impaired individuals with similar audiograms.

Acknowledgments

This work was supported by Grants R01 DC00184 and P50 DC00422 from NIH/NIDCD; the South Carolina Clinical & Translational Research (SCTR) Institute, with an academic home at the Medical University of South Carolina, NIH/NCRR Grant UL1 RR029882; and the James E. and Pamela Knowles Foundation. This investigation was conducted in a facility constructed with support from Research Facilities Improvement Program Grant

C06 RR14516 from the National Center for Research Resources, National Institutes of Health.

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¹See supplementary material at <http://dx.doi.org/10.1121/1.3693386> for a table that provides individual subjects' quiet thresholds, ages, background noise levels, and corresponding masked thresholds used to calculate masking slopes, which will be discussed further.

²For example, when the level within an ERB was 50 dB SPL, the overall level was 59 dB SPL for the 1000-Hz-wide signal and 62 dB SPL for the 2000-Hz-wide background noise. The N_0 was 21 dB below the level within the 1000-Hz ERB.

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