Recovery from on- and off-frequency forward masking in listeners with normal and impaired hearing

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The aim of this study was to investigate the possible mechanisms underlying an effect reported earlier [Wojtczak, M., and Oxenham, A. J. (2009). J. Acoust. Soc. Am. **125**, 270–281] in normal-hearing listeners, whereby recovery from forward masking can be slower for off-frequency tonal maskers than for on-frequency tonal maskers that produce the same amount of masking at a 0-ms masker-signal delay. To rule out potential effects of confusion between the tonal signal and tonal masker, one condition used a noise-band forward masker. To test whether the effect involved temporal build-up, another condition used a short-duration (30-ms) forward masker. To test whether the effect is dependent on normal cochlear function, conditions were tested in five listeners with sensorineural hearing loss. For the 150-ms noise maskers, the data from normal-hearing listeners replicated the findings from the previous study that used tonal maskers. In contrast, no significant difference in recovery from on- and off-frequency masking was observed for the 30-ms tonal maskers in normal-hearing listeners, or for the 150-ms tonal maskers in hearing-impaired listeners. Overall, the results are consistent with a mechanism based on efferent feedback that affects the recovery from forward masking in the normal auditory system.
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I. INTRODUCTION

Much effort in the past decade has gone into developing behavioral estimates of basilar-membrane (BM) compression in human listeners, with the long-term goals of improving our understanding of human cochlear mechanics, and of providing more accurate diagnoses of cochlear hearing loss (Oxenham and Plack, 1997; Plack and Oxenham, 2000; Nelson *et al.*, 2001; Lopez-Poveda *et al.*, 2003; Plack and O'Hanlon, 2003; Rosengard *et al.*, 2005; Lopez-Poveda and Alves-Pinto, 2008). A method based on the measurement of temporal forward masking curves, termed the TMC method (e.g., Nelson *et al.*, 2001; Lopez-Poveda *et al.*, 2003; Plack *et al.*, 2004) has been favored as it can be used over a wide range of frequencies, and it uses a fixed low signal level, which reduces some of the problems associated with using higher signal levels, such as "off-frequency listening" (Patterson and Nimmo-Smith, 1980; O'Loughlin and Moore, 1981). The method involves measuring the forward masker level needed to just mask the signal as a function of the temporal gap between the masker and the signal. The assumptions of this method are that the signal is detected by vibrations at a place along the BM with a characteristic frequency (CF) corresponding to the signal frequency, and that responses to maskers an octave or more below the signal frequency are unaffected by BM compression, at least for high (≥ 4 kHz) signal frequencies. The effect of increasing the gap on masker levels at threshold is thought to reflect the combined effect of post-cochlear recovery from forward masking and BM compression for maskers at or near the signal frequency (on-frequency masking), but is thought to reflect only the effects of post-cochlear recovery from forward masking for maskers well below the signal frequency (off-frequency masking). In this way, it is possible to derive the estimated BM input-output function by comparing on- and off-frequency TMCs (Nelson *et al.*, 2001; Lopez-Poveda *et al.*, 2003; Plack and Drga, 2003). The method is thought not to be valid at frequencies much lower than 4 kHz, because BM compression at these lower CFs may extend down to frequencies an octave or more below the signal frequency. If the response to off-frequency maskers at lower CFs is compressive, then using these maskers to obtain a linear reference would overestimate the compression exponent (suggesting less compression) at the signal CF place. In such cases the TMC for the off-frequency masker measured using a high signal frequency (≥ 4 kHz) has been used as a linear reference when deriving BM input-output functions at lower CFs (Lopez-Poveda *et al.*, 2003; Plack and Drga, 2003).

Using an off-frequency TMC measured for a high signal frequency as a linear reference at other signal frequencies implicitly relies on an assumption that the post-cochlear recovery from forward masking does not depend on the frequency region. Although frequency-independent recovery has found support in some data (Lopez-Poveda and Alves-Pinto, 2008; Plack *et al.*, 2008), the assumption was challenged by Stainsby and Moore (2006), who suggested that post-cochlear recovery from forward masking may occur at a faster rate at low than at higher frequencies. Their finding implies that a reference TMC obtained in a high-frequency region may not accurately represent the rate of recovery from forward masking at lower frequencies. Recently, Wojtczak and Oxenham (2009) examined the validity of another implicit assumption: That recovery from forward masking,

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measured psychophysically for a given signal frequency, does not depend on the masker frequency and level so long as the maskers have the same temporal characteristics (duration and separation from signal) and produce the same excitation on the BM at the CF corresponding to the signal frequency. This assumption is central to the TMC method, in which BM input-output functions are derived assuming that changes in level of the off-frequency masker directly represent changes of the BM response to the on-frequency masker that are needed to maintain masking as the masker-signal gap is increased. Wojtczak and Oxenham (2009) found that the assumption held at moderate masker levels, but when the level of the off-frequency masker exceeded 90 dB SPL the recovery was slower than that for an on-frequency masker adjusted in level to yield the same masked threshold at a 0-ms masker-signal delay. The two maskers were (and will be hereafter) referred to as "equivalent" because the same masked threshold at a 0-ms delay presumably indicated that the maskers produced the same excitation at the signal CF place on the BM. Predictions from the data in the study of Wojtczak and Oxenham (2009) suggested that the TMC method may lead to overestimating the amount of BM compression, particularly when high levels of the off-frequency masker are used.

The first aim of the present study was to gain insight into the mechanism(s) responsible for the difference between the rates of recovery for on- and off-frequency maskers at high masker levels. As mentioned above, the measured recovery functions are thought to reflect combined effects of BM compression and the rate of post-cochlear recovery from forward masking. Psychophysical recovery functions may also be affected by a host of other effects originating from different sites along the auditory pathways, from pre-cochlear (e.g., the middle-ear acoustic reflex), through cochlear (e.g., a feedback-based reduction of cochlear gain due to medial olivocochlear efferents activation) to post-cochlear (for example, neural saturation or perceptual confusion). Any effect that differentially affects psychophysically measured rates of recovery from forward masking for on- versus off-frequency maskers would provide a confounding factor in estimating BM compression. Wojtczak and Oxenham (2009) considered some of these effects as a possible explanation for the difference between the recovery rates they observed for high masker levels. The first was that "confusion" effects between the on-frequency masker and the signal (Moore and Glasberg, 1982; Neff, 1986) may have reduced masker levels at threshold for short masker-signal gap durations, thereby leading to a seemingly faster recovery from forward masking. This seemed unlikely for several reasons. First, the difference between on- and off-frequency maskers was only found for a high-level masker with a frequency well below that of the signal; for lower masker levels, and for off-frequency maskers above the signal frequency, the recovery rates were the same. Second, a contralateral high-frequency tone was gated synchronously with the masker to reduce any influence of confusion. Finally, in earlier studies confusion effects have only been observed consistently for narrowband noise maskers but not for tonal maskers (Neff, 1986). Nevertheless, it remains possible that some confusion may have contributed to the results. The second possible mechanism involved the middle-ear muscle reflex (MEMR) and/or the medial olivocochlear reflex (MOCR). Both reflexes involve descending pathways that originate from the superior olivary complex and affect peripheral responses. Activation of the MEMR results in an increase in middle-ear impedance, which in turn adversely affects transmission of the stimulus through the middle ear. One possibility is that the MEMR could affect the transmission of a later portion of the masker (for sufficiently long maskers) and the signal, with both being effectively attenuated. Irrespective of whether the attenuation of the final portion of the masker would affect the signal level at masked threshold, activation of the MEMR might slow down recovery from forward masking observed psychophysically since the decay of the effect of muscle contraction extends over an interval of 300 to 700 ms after the offset of the stimulus that elicited the MEMR (Green and Margolis, 1984). Thus, if the MEMR played a role, recovery from forward masking, as measured psychophysically, could be slower. The MOCR is thought to operate by reducing cochlear gain, as determined by the outer hair cells. Activation of the MOCR by the masker could lead to a reduction in cochlear gain at the signal place and a decrease in the response to the signal (Cooper and Guinan, 2006). According to the time course described by Backus and Guinan (2006), the decay of the effect of MOCR activation occurs with an approximately 25-ms delay from the offset of the elicitor (masker, in this study). In addition, as a result of a reduced gain due to MOCR activation, the BM response to the signal would become more linear. Since recovery from forward masking observed psychophysically is thought to be determined by a combination of the BM response growth and post-cochlear recovery (Plack and Oxenham, 1998), a less compressive response or a change in the level at which the response changes from linear to compressive (Plack *et al.*, 2004) would lead to an apparently slower decay of forward-masked threshold with increasing masker-signal delay (see, e.g., Oxenham and Moore, 1997). Thus, MOCR activation would result in a slower recovery from forward masking, as observed psychophysically.

In addition to having relatively long time constants, the two reflexes are typically elicited more effectively by wide noise bands than by pure tones with the same rms levels (for a review of the MEMR and MOCR, respectively, see Hellman and Scharf, 1984; Guinan, 2006). Experiment 1 measured the recovery from forward masking using long-duration noise maskers and short-duration tonal maskers in normal-hearing listeners. If confusion played a role in the initial results of Wojtczak and Oxenham (2009), then the use of wideband (1600-Hz-wide) noise maskers should eliminate the difference between the rates of recovery for on- versus off-frequency maskers; on the other hand, if efferent MOCR or MEMR effects played a role, the use of noise may lead to an increased difference since noise is a more effective elicitor than a tone for the two reflexes. The short-duration tonal maskers were also used to test the idea that MOCR or MEMR activation played a role: Given the relatively long time constants associated with the activation of the reflexes, short-duration maskers should be less effective in eliciting their response than longer maskers, and so the difference between the on- and off-frequency forward masking curves should be reduced. It should be mentioned that reduced masker duration could also reduce temporal confusion due to an improvement of duration discrimination with decreased reference duration of a stimulus (Abel, 1972). However, results from our previous study (Wojtczak and Oxenham, 2009) suggested that a role of confusion was less likely, as discussed above.

High-level maskers are often used when testing hearing-impaired (HI) listeners using the TMC method. One possible implication from the findings of Wojtczak and Oxenham (2009) is that the amount of residual compression might be overestimated in HI listeners with mild to moderate hearing losses (Plack *et al.*, 2004). On the other hand, if MOCR activation mediates the effect, then HI listeners who have reduced cochlear gain should show a reduction or elimination of the effect, depending on the amount of residual cochlear gain. The second aim of this study was therefore to test whether differences between rates of recovery from forward masking by on- and off-frequency maskers are also found in HI listeners, which, if present, may lead to overestimates of the amount of BM compression when using the TMC method. Experiment 2 measured forward masking for on- and off-frequency maskers as a function of the masker-signal gap in a group of five HI listeners.

II. EXPERIMENT 1: RECOVERY FROM FORWARD MASKING BY EQUIVALENT NOISE MASKERS AND SHORT TONAL MASKERS IN NORMAL-HEARING LISTENERS

A. Stimuli and procedure

Detection thresholds were measured for a 10-ms 4-kHz signal presented in quiet and in the presence of on- or off-frequency forward maskers. The signal was gated with 5-ms ramps with no steady-state portion. Thresholds were measured using a three-interval, three-alternative forced-choice (3AFC) procedure, coupled with an adaptive tracking technique that estimates the 70.7% correct point on the psychometric function (Levitt, 1971). For thresholds measured in quiet, the signal appeared randomly in one of the three observation intervals while the other two contained silence. In the forward-masking task, the masker appeared in all three observation intervals and the signal followed the masker in one interval, chosen randomly for each trial. The listener's task was to indicate which interval contained the signal. The three intervals were marked by lights on a computer screen and visual feedback was provided after each response. The observation intervals were separated by 500-ms silent intervals. At the beginning of each run, the signal was presented at a clearly audible level. The level was decreased by 8 dB after two consecutive correct responses and increased by the same step size after each incorrect response until the second reversal was obtained. The step size was decreased by a factor of 2 after every two reversals until it reached 2 dB. After that, the step size was held constant for the remaining eight reversals. A run terminated after 12 reversals and a threshold estimate was obtained by averaging the signal levels at the last 8 reversals. Three thresholds obtained from single runs were averaged to compute the final threshold estimate for each subject and condition. A noise consisting of two bands placed around the signal frequency was used to prevent off-frequency listening (O'Loughlin and Moore, 1981). The lower band extended from 2260 to 3200 Hz; the upper band extended from 5200 to 6200 Hz. These and all other noises used in the experiments within this study were created from Gaussian noise that was generated in the spectral domain and was filtered by setting the amplitudes of components outside the passband to zero, so that only the gating on and off of the noise limited the steepness of the spectral slopes. The level of the noise was varied with the level of the signal during the adaptive tracking procedure, to remain 20 dB below the level required to mask the signal, as determined individually in pilot testing prior to the main experiment (for details on determining the background noise level see Wojtczak and Oxenham, 2009). A new sample of noise was used in each trial. The noise started 300 ms before the beginning of the first observation interval and ended with the end of the third observation interval. Because the level of the background noise was kept 20 dB below that needed to mask the signal and the overall noise level in dB SPL was generally lower than the signal level during the tracking procedure, suppression of the BM response to the signal by the background noise was likely negligible (Shannon, 1976). It should be noted however, that even if the noise had a suppressive effect on the signal, the effect would have been the same for the on- and off-frequency maskers at a 0-ms delay, since recovery functions were measured for masked thresholds equated for that delay. It follows that suppression of the signal by the noise would have been the same for all delays if the rates of recovery were the same for the two maskers.

Before measuring recovery from forward masking, the levels of the on- and off-frequency maskers presumed to produce the same excitation on the BM at the signal CF place were first determined. The level of the off-frequency masker was fixed and the threshold for detecting the signal was measured at a 0-ms delay between the masker offset and signal onset. Three single-run threshold estimates were averaged to obtain the final threshold. Next, the signal level was fixed at that estimated threshold value and the level of the on-frequency masker necessary to just mask the signal presented with a 0-ms delay was measured using the 2-up, 1-down adaptive tracking. The step sizes for changing the masker level during the tracking were the same as those used in conditions where the signal level was varied adaptively. Masker levels obtained from three single runs were averaged to obtain the final estimate of the level of the on-frequency masker (L_{on}) that was equivalent at a 0-ms delay to the off-frequency masker. Subsequently, recovery functions were measured for the off-frequency masker and the on-frequency masker with a level of L_{on}, using masker-signal offset-onset delays between 0 and 115 ms. In each experimental condition except for detecting the signal in quiet, a 70-dB 7-kHz tone, gated on and off with the masker, was presented to the contralateral ear to further reduce any potential effects of temporal confusion. The level of the contralateral tone was chosen to ensure that the tone was audible in each condition during the experiment. A frequency well above 4 kHz was chosen to avoid the possibility that the cuing tone would affect detectability of the signal through the contralateral MEMR or MOCR activation. Indeed, the pilot measurements showed that the 70-dB SPL 7-kHz tone had no effect on threshold for detecting the 4-kHz probe when the on- and off-frequency maskers were absent.

The stimuli were generated digitally on a PC with a sampling rate of 48 kHz and played out via a 24-bit Lynx-Studio Lynx22 sound card. The stimuli were presented to the left ear via the earphone of a Sennheiser HD 580 headset. The listeners were tested in a double-walled sound-attenuating booth and responded via a computer keyboard or a mouse. Further details of the noise maskers and short tonal maskers are given below.

1. Noise maskers

The on- and off-frequency filtered Gaussian-noise maskers both had the same bandwidth of 1600 Hz. The on-frequency masker extended from 3200 to 4800 Hz, and the off-frequency masker extended from 800 to 2400 Hz. The duration of the maskers was 150 ms including 5-ms raised-cosine onset/offset ramps. Two levels of the off-frequency masker were used, 92 and 83 dB SPL. For each level of the off-frequency masker, the level of the on-frequency masker producing the same masked threshold at a 0-ms masker-signal delay was found, as described above. For each of the four maskers (two levels of the off-frequency masker and two levels of the on-frequency masker), recovery functions were measured for masker-signal delays between 0 and 115 ms.

2. Short tonal maskers

The tonal maskers were 30-ms in duration, including 5-ms raised-cosine ramps. Only one level of the 2.4-kHz masker, 92 dB SPL, and one level of the equivalent on-frequency masker were used.

B. Listeners

Nine listeners (6 females, 3 males) participated in the experiment. Their ages ranged from 20 to 32 years. All had normal hearing as evidenced by their thresholds in quiet measured using an ANSI certified audiometer (Madsen Conera, GN Otometrics, Shaumburg, IL). The listeners had thresholds that were below 15 dB HL for audiometric frequencies between 0.25 and 8 kHz. All the listeners were recruited from the college student population and were paid for their participation. One listener had also participated in our previous study (Wojtczak and Oxenham, 2009). Not every listener participated in every condition due to limited availability. The listeners received at least 2 h of practice before data collection commenced.

C. Results

Recovery functions for the 92-dB SPL off-frequency noise masker and the equivalent on-frequency masker for six normal-hearing listeners are shown in Fig. 1. The symbols represent the signal levels at threshold, the solid and dashed curves represent the best power-function fits to the data,[1] and the dashed-dotted horizontal lines represent thresholds for detecting the 10-ms 4-kHz signal in quiet. For each listener, the level of the on-frequency masker that produced a similar amount of masking to that produced by the 92-dB SPL off-frequency masker is provided in the legend in each panel.

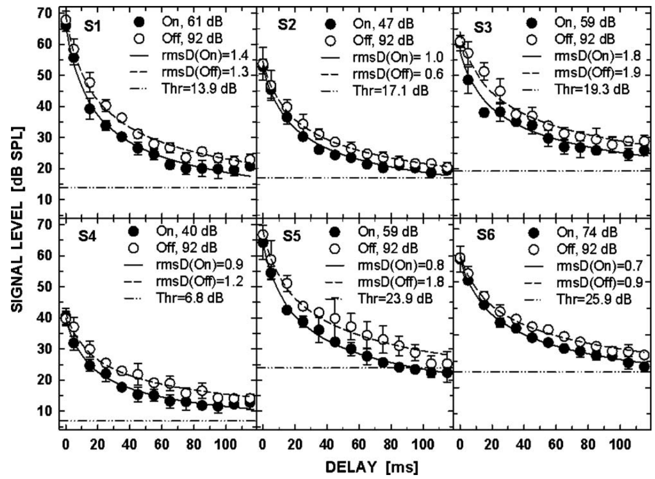

FIG. 1. Recovery from forward masking for the 92-dB SPL off-frequency noise masker and the equivalent on-frequency noise masker in normal-hearing listeners. The solid and dashed lines show power-function fits to the masked thresholds. The dashed-dotted line represents threshold for detecting the signal in quiet. Levels of the maskers, rms deviations (rmsD) from the fitted curves and the values of absolute thresholds (Thr) are provided in the legend in each panel.

Despite the overlap of thresholds measured for the on- and off-frequency maskers at a 0-ms delay, the recovery functions diverge and the thresholds for the off-frequency masker (open circles) consistently fall above those for the on-frequency masker (filled circles). The power-function fits provide a reasonably good description of the data as indicated by small rms deviations of the data from the fitted lines. Overall, the data suggest that for the 92-dB SPL off-frequency masker, recovery from forward masking is somewhat slower than that for the equivalent on-frequency masker, even though the two maskers presumably produced comparable amounts of excitation on the BM, based on signal thresholds at a 0-ms delay.

Figure 2 shows the signal thresholds and power-function fits for the 83-dB SPL off-frequency masker and the equivalent on-frequency masker. Three listeners (S1, S3, and S4) exhibited a trend for the off-frequency masker to produce a slower recovery, but the difference between the recovery functions was smaller than for the 92-dB SPL off-frequency masker.

The first two panels of Fig. 3 show the best-fitting values of parameter b, which governs the slope in the power-function fit, for the high-level (HL, 92 dB SPL) and low-level (LL, 83 dB SPL) off-frequency maskers (gray bars) and their equivalent on-frequency maskers (black bars). For the HL condition (left panel), the gray bars are consistently lower than the black bars, indicating slower recovery from forward masking for the off-frequency masker. A paired t-test performed on the values of parameter b for off- and

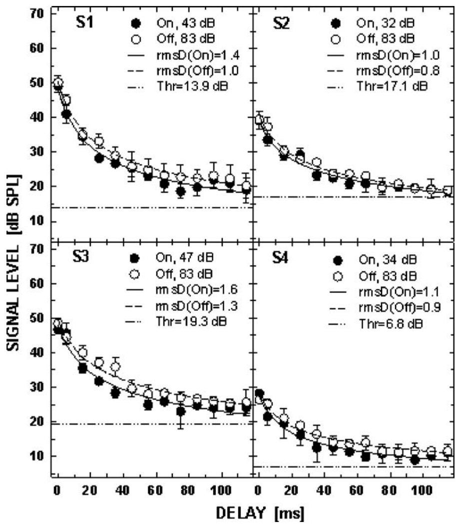

FIG. 2. As in Fig. 1 but for the off-frequency noise masker set at a lower level (83 dB SPL).

on-frequency maskers revealed that the difference between the slopes of the fitted functions was statistically significant $[t(5)=4.69,\ p=0.005]$.

For the LL condition (middle panel), three of the four listeners tested exhibited slightly smaller recovery slopes for the off-frequency masker (gray bars shorter than black bars), but the difference between the slopes for the four listeners did not reach significance $[t(3)=1.99,\ p=0.141]$. Since four listeners were tested in the LL condition and six listeners were tested in HL condition, a t-test for the latter was re-run using only the data from the four listeners who completed the LL condition. The difference between the slopes in the HL condition remained statistically significant for the four listeners $[t(3)=4.69,\ p=0.02]$, which implies that the different statistical outcomes for the two conditions were not due solely to the difference in statistical power.

Figure 4 shows data for the 30-ms tonal maskers obtained for five NH listeners. No systematic difference between the rates of recovery was apparent in the data. The b values are shown in the rightmost panel of Fig. 3. A paired t-test performed on the exponents b did not show significant differences in recovery for the on- versus off-frequency maskers $[t(4)=0.67,\ p=0.519]$. Since the difference between recovery for the on- versus off frequency tonal maskers was significant for a 150-ms masker duration in the

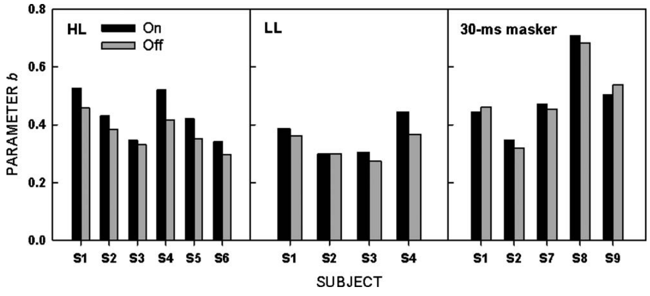

FIG. 3. The bars represent the values of the exponent in the power-function fits shown in Figs. 1, 2, and 4 for NH listeners. The left and middle panels are for the high-level (92 dB SPL) and low-level (83 dB SPL) off-frequency maskers, respectively. The right panel is for the 30-ms tonal maskers.

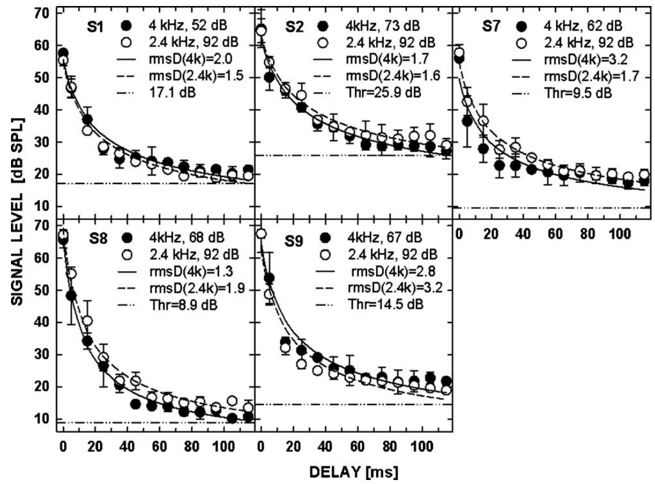

FIG. 4. As in Fig. 1 but for 30-ms pure-tone maskers.

study of Wojtczak and Oxenham (2009) but that difference was not significant for the same tonal maskers with a shorter duration (30 ms) in this study, an independent-samples t-test was performed to determine whether there was a significant effect of masker duration on the difference in on- versus off-frequency recovery rate. The t-test performed on the ratios of b values[2] showed a significantly greater effect for the 150- than 30-ms masker duration $[t(9)=3.05,\ p=0.013]$. An independent-samples t-test was also performed on the ratios of b values for the 150-ms noise maskers in the HL condition in this study and the 150-ms tonal maskers in the HL condition in the study of Wojtczak and Oxenham (2009). The t-test showed no significant difference between the two types of maskers $[t(10)=1.35,\ p=0.206]$.

D. Discussion

Previous studies have assumed that for maskers producing the same excitation on the BM at the signal CF place, recovery from forward masking measured psychophysically is independent of the masker frequency; the same excitation should lead to the same masked threshold at any masker-signal delay. In this experiment, levels of on- and off-frequency maskers were adjusted to produce the same masked threshold at a 0-ms delay. Since the maskers produced the same amount of masking and had the same temporal envelope characteristics, it was assumed that they excited the signal CF place equally. However, as shown in Fig. 1, recovery functions for the on- and off-frequency maskers did not overlap for gaps longer than 0 ms, and thresholds were consistently higher for the 92-dB SPL off-frequency masker than for the equivalent on-frequency masker. The results replicate the finding by Wojtczak and Oxenham (2009) where the same trend was found for tonal maskers. The fact that similar trends are seen for both tonal and noise maskers makes an explanation based on confusion effects less likely, as 1.6-kHz-wide noise bands are unlikely to have been confused with the tonal signal.

The data in Fig. 4 showed that for tonal maskers with short durations (30 ms) recovery rates did not display a significant dependence on the masker frequency, unlike the recovery rates for the 150-ms noise maskers, and 150-ms tonal maskers in the study of Wojtczak and Oxenham (2009). The mechanism responsible for the difference between on- and off-frequency forward-masking recovery rates may therefore require some "build-up" time. This result is consistent with the influence of the reflexes outlined in the Introduction. One such reflex is the MEMR. The mean MEMR threshold for a 2-kHz elicitor, measured in normal-hearing listeners using a 226-Hz probe is around 95 dB SPL (Feeney *et al.*, 2003). For a noise elicitor, the level needed for threshold acoustic reflex activation is lower and depends on the noise bandwidth (Green and Margolis, 1984). The build-up time at threshold of the MEMR activation decreases with increasing stimulus level reaching values of 25–35 ms at levels 40 dB above threshold for reflex activation (Moller, 1974). This implies that a 30-ms 92-dB masker would be unlikely to elicit the reflex, whereas the 150-ms masker could produce an effect of reflex activation on recovery from forward masking. Due to a relatively long decay of the effect of the MEMR (300 to 700 ms, as reported by Green and Margolis, 1984), the recovery from forward masking measured psychophysically may be slower in the presence of the reflex activation. The effect of the MEMR would be more likely to influence the recovery rate for the off-frequency masker because of the masker's higher level. Although the MEMR can be elicited by a relatively wide range of frequencies, the change in stiffness of the ossicular-chain mechanism due to the stapedius muscle contraction influences transmission of frequencies primarily below 2 kHz and has not normally been shown to attenuate higher frequencies (Møller, 1965). However, a few studies have shown that transmission of high frequencies might be affected as a result of decoupling between the cochlea and the middle ear (for a review see Moller, 1984). Thus, even though a relatively high signal frequency was used in all conditions tested, the masker with frequencies at and around 2.4 kHz could activate the MEMR and could, due to the decoupling, decrease the transmission of the 4-kHz probe following the masker. The effect of the decoupling shown in physiological studies of transmission through the middle ear in the presence of the MEMR was typically small (a few decibels of attenuation), however, its potential to cause differences in recovery from forward masking by on- and off-frequency maskers cannot be completely ruled out without more direct measurements.

An alternative mechanism that could play a role is the MOCR. The characteristics of the MOCR in humans have been studied by measuring the effect of efferent activation on changes in the amplitude of otoacoustic emissions (for a review see Guinan, 2006). Recently, Backus and Guinan (2006) measured the time course (build-up and decay) of the effect of efferent activation on the amplitude of stimulus frequency otoacoustic emissions (SFOAEs). Their data show that the effect starts with a delay of 25 ms from the onset of the elicitor and builds up exponentially with a time constant of approximately 70 ms. This time course is consistent with the presence of the difference between the rates of recovery from forward masking for the 150- and not for 30-ms maskers, assuming the build-up of the effect of efferent activation does not continue after the termination of the masker. Although in the study of Backus and Guinan (2006) the elicitor was continuously present during the measurement of the build-up time, we are not aware of any mechanism for which a build-up would continue after the stimulus has ended. Under this assumption, the 30-ms masker would not be sufficiently long to allow for a full build-up of the MOCR effect and the effect would decay after the masker offset following a 25-ms delay (Backus and Guinan, 2006). Consequently, the effect elicited by the 30-ms masker would not be as strong as that elicited by the 150-ms masker.

For tonal elicitors, the MOCR produces a significant effect on OAEs only for high elicitor levels (Berlin *et al.*, 1993). In order to account for the slower recovery from forward masking by an off-frequency masker, it would have to be assumed that the MOCR elicited by the off-frequency masker would have an effect on the cochlear gain of the response to the signal whose frequency was nearly an octave above that of the masker. Measurements of the effect of efferent activation by a contralateral acoustic stimulus on auditory-nerve responses in animals do not provide a support for such an assumption (e.g., Warren and Liberman, 1989). In humans, Lilaonitkul and Guinan (2009) showed that an elicitor of the MOCR can produce a greater change in the amplitude of the SFOAE for a probe with a frequency half-an-octave to an octave above that of the elicitor than for a probe with a center frequency of the elicitor band. However, the shift of the maximum MOCR effect toward higher frequencies was observed for contralateral but not for ipsilateral elicitors of the reflex. Although in the forward masking experiment the masker and signal were presented to the same ear (ipsilaterally), the MOCR elicited by a high-level ipsilateral off-frequency masker may have produced a stronger effect at the signal CF than the equivalent but lower-level on-frequency masker.

For a given stimulus intensity, the effect of the MEMR is stronger when the bandwidth of the stimulus is wider (Hellman and Scharf, 1984). The same is true for the MOCR (Guinan, 2006). Assuming that either of the two mechanisms is responsible for the differences in recovery between on- and off-frequency maskers, one might expect that larger differences in recovery rates should be observed for noise than for tonal maskers. However, the differences observed for the 150-ms noise maskers were comparable to those observed for the tonal maskers in the study of Wojtczak and Oxenham (2009). This result for noise maskers would make the MEMR a less likely candidate for the mechanism underlying the difference in recovery from forward masking, since the effect of the stapedius muscle contraction should be stronger for the noise than tonal off-frequency maskers with equal levels. In contrast, the effect of MOCR activation exhibits tuning similar to or somewhat broader than the tuning of the BM filters (Guinan, 2006). Since the off-frequency noise masker extended from 800 to 2400 Hz, it is possible that only the upper part of the bandwidth contributed to the effect of the MOCR on the gain of the BM response to the 4-kHz signal. If that were the case, the "effective" elicitor level would be less than 92 dB SPL and thus could offset the advantage of a wider elicitor bandwidth. In the study of Wojtczak and Oxenham (2009) masked threshold measured at a 0-ms masker-signal delay for the 92-dB SPL off-

TABLE I. The age of the hearing-impaired listeners and their audiometric thresholds in dB HL at octave frequencies expressed in kHz.

Subject	Age	0.25	0.5	1	2	4	8
HI1	68	35	35	35	45	45	60
HI2	74	20	30	30	50	65	55
HI3	48	40	50	60	75	60	55
HI4	73	30	35	40	60	65	70
HI5	64	45	50	55	50	50	75

frequency tonal masker averaged across the listeners was 68 dB SPL, whereas the average masked threshold for the 92-dB SPL noise masker in this study was 59 dB SPL. Assuming that the masked threshold at a 0-ms masker-signal delay reflects the amount of masker excitation at the signal CF place, it could be concluded that the noise masker evoked less excitation than the tonal masker in the filter tuned to the signal frequency. Thus, the differences in recovery observed for the on- and off-frequency noise maskers could be smaller than they would have been for maskers producing excitation levels comparable to those for tonal maskers in our previous study. Unfortunately, higher excitation levels would require higher levels of the noise maskers which could not be used due to uncomfortable loudness levels.

Based on the present and earlier data (Wojtczak and Oxenham, 2009), it is not possible to determine whether either reflex (or both) played a role. More direct measurement of MEMR or MOCR activation could be made using SFOAEs and examining the changes in phase of the ear-canal pressure due to the masker in the different conditions tested here (Guinan *et al.*, 2003). Regardless of the underlying mechanism, it is important to know whether similar effects are found in HI listeners in order to evaluate whether such effects could influence estimates of BM compression obtained using the psychophysical TMC method for these listeners. This question was addressed in experiment 2.

III. EXPERIMENT 2: RECOVERY FROM FORWARD MASKING BY EQUIVALENT ON- AND OFF-FREQUENCY TONAL MASKERS IN HEARING-IMPAIRED LISTENERS

A. Stimuli and procedure

Detection thresholds were measured for a 10-ms 4-kHz signal presented in quiet and in forward masking by a 4-kHz (on-frequency) masker and a 2.4-kHz (off-frequency) masker. The sinusoidal maskers had a duration of 150 ms and were gated on and off with 5-ms raised-cosine ramps. The signal was also gated with 5-ms ramps with no steady-state portion. The off-frequency masker was presented at a level of 92 dB SPL. Aside from the use of the longer tonal maskers to match those used by Wojtczak and Oxenham (2009), the same procedures and stimuli were used for measuring thresholds as described in experiment 1, including the noise to reduce off-frequency listening and the contralateral 7-kHz tone that was gated on and off with the masker to reduce potential confusion effects.

B. Listeners

Five listeners with mild or moderate to moderately severe cochlear hearing losses participated in the experiment. The cochlear site of hearing loss was evidenced by smaller than 10-dB air-bone conduction gap, normal tympanograms and a lack of roll-off in the speech performance-intensity function at high levels. The listeners' ages and their audiometric thresholds in the left ear used for testing are given in Table I. All the listeners had symmetric hearing losses (approximately equal thresholds in both ears) and had no previous experience with psychophysical tasks. The listeners were given about 2 h of practice until their thresholds stabilized.

C. Results

Results for the HI listeners are shown in Fig. 5. Masked thresholds are plotted as a function of the masker-signal delay for the 4-kHz masker (filled symbols) and the 2.4-kHz masker (open symbols). The solid and dashed lines represent the best power-function fit to the respective recovery functions. The horizontal dashed-dotted lines represent thresholds for detecting the 10-ms 4-kHz probe in quiet. The legend in each panel shows on- and off-frequency masker levels that produced similar amounts of masking at a 0-ms masker-signal delay. The rms deviations of the data from the fitted functions, also shown in the legend, indicate that the power functions accurately represent the shape of recovery from forward masking. For listeners HI1, HI3, and HI4 the data and the fitted functions from the two conditions overlap. For listener HI2, there is a slight (about 2 dB) difference between

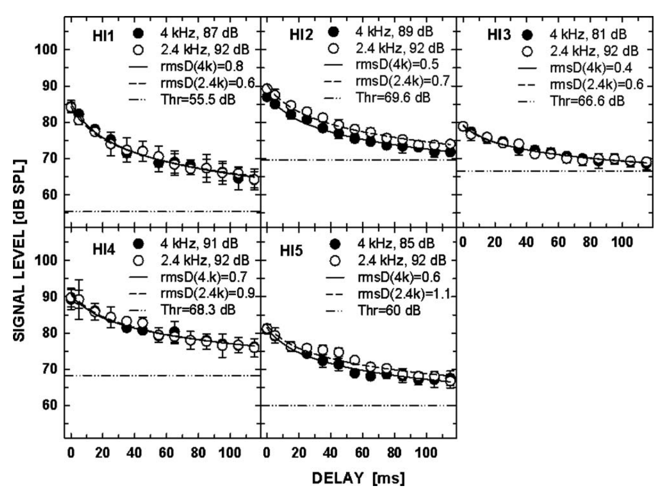

FIG. 5. Recovery from on- and off-frequency forward masking in five HI listeners. Symbols and lines are as in Fig. 1.

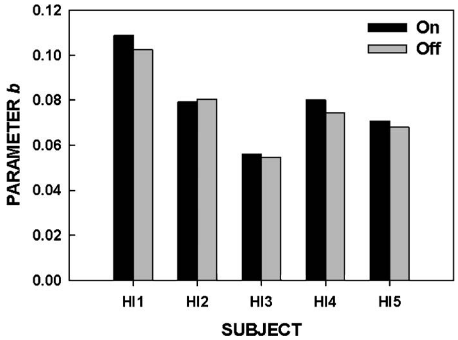

FIG. 6. Values of the exponent in the power-function fits shown in Fig. 5 for HI listeners.

thresholds for the 4- and 2.4-kHz maskers at a 0-ms delay, but the fitted functions are essentially parallel, indicating that the recovery rates are similar for the two maskers. Listener HI5 showed a very small difference in recovery. The *b* values of the best-fitting power functions are shown in Fig. 6. A paired t-test performed on the exponents of the fitted power functions for the 4- and 2.4-kHz maskers indicated that the exponents were not significantly different for the group [$t(4)=1.06$, $p=0.348$]. Thus, in contrast to normal-hearing listeners under the same conditions (Wojtczak and Oxenham, 2009), the HI listeners tested here did not as a group show a difference in recovery functions between on- and off-frequency forward maskers. An independent-samples t-test comparing ratios of *b* values for on- and off-frequency maskers for the five HI listeners in the present study and for the six listeners with normal hearing from the study of Wojtczak and Oxenham (2009) which used the same stimuli, showed that the effect of the masker frequency on recovery was significantly different for the two groups of subjects [$t(9)=3.42$, $p=0.008$].

D. Discussion

The finding by Wojtczak and Oxenham (2009) that NH listeners exhibit different rates of recovery from on- and off-frequency masking for maskers presented at high levels when the effect of compression is factored out raised the question of whether substantial amounts of residual compression estimated from the TMCs in HI listeners (Plack *et al.*, 2004) may have been influenced by similar differences between recovery rates. The data in Fig. 5 show that at least some HI listeners do not exhibit significant differences in recovery from forward masking and thus their compression estimates obtained using the TMC method would not be affected. Given the small number of the HI listeners in this study, it cannot be concluded that listeners with cochlear hearing losses do not generally exhibit these differences. Instead, the effect of the mechanism underlying the differences in the course of recovery may depend on the degree of cochlear damage. The values of exponent *b* in the fitted power functions[1] were on average about a factor of 7 smaller than those in functions fitted to the NH data by Wojtczak and Oxenham (2009) for comparable maskers (92-dB SPL 2.4-kHz masker and the equivalent 4-kHz masker). The slow recovery from forward masking may reflect reduced compression of the basilar-membrane response (Oxenham and Moore, 1997; Plack and Oxenham, 1998) and higher asymptotic threshold values in the HI listeners (Glasberg *et al.*, 1987). Aside from changes in cochlear function, the average age of our HI listeners (65 years) was much higher than that of our NH listeners (23 years). A number of studies have also suggested that age, independent of hearing loss, may negatively affect temporal processing (e.g., Fitzgibbons *et al.*, 2007; Gifford *et al.*, 2007).

The nearly perfect overlap of the on- and off-frequency recovery functions suggests that confusion due to perceptual similarity between the on-frequency masker and the signal did not play a role. The lack of effect of masker frequency in the data from HI listeners is also consistent with the expected effects of one (or both) of the acoustic reflexes. Threshold for the MEMR activation is increased in individuals with moderate to moderately severe hearing losses compared to those with normal hearing (Beedle and Harford, 1973; Silman *et al.*, 1978). In addition, HI listeners exhibit a reduced effect of the MEMR activation above the threshold, for comparable stimulus levels. The mean threshold for activation of the MEMR for a 2-kHz tone in normal-hearing listeners is around 92–95 dB SPL (Silman *et al.*, 1978; Feeney *et al.*, 2003). For comparison, the threshold for a HI listener with a severe hearing loss of 59 dB HL at 2 kHz in the study of Silman *et al.* (1978) was near 100 dB SPL. These data support the idea that in this study, the off-frequency maskers could elicit the MEMR in the normal-hearing listeners, but the same level was not sufficient to elicit the reflex in the HI listeners. It is possible that the HI listeners might have shown a reduced rate of recovery for the off-frequency masker if a higher level of the masker had been used.

The MOCR has the effect of turning down cochlear gain (Guinan, 2006). For listeners with a reduced or absent gain, efferent activation by a high-level masker would be expected to have little or no effect on the BM response to a signal that follows the masker. Thus, if the difference in recovery from forward masking in NH listeners, measured for on- and off-frequency maskers is mediated by the MOCR, a negligible or no difference should be seen in listeners with cochlear hearing loss, consistent with the data in experiment 2.

IV. CONCLUSIONS

Recovery from forward masking was measured using 150-ms noise maskers and 30-ms tonal maskers for NH listeners, and 150-ms tonal maskers for HI listeners. In each condition recovery from forward masking was compared for a pair of maskers, an off-frequency masker and an on-frequency masker, whose levels were set to produce the same masked threshold at a 0-ms masker-signal delay. The following conclusions can be drawn from the data.

(1) For noise maskers, NH listeners exhibit differences in recovery rates for on- and off-frequency maskers that are equivalent at a 0-ms masker-signal delay, when the off-frequency masker is presented at 92 dB SPL, but not when its level is 83 dB SPL. This result is consistent with the findings for tonal maskers in the previous study by Wojtczak and Oxenham (2009).

(2) For short-duration (30-ms) tonal maskers, NH listeners do not exhibit differences between recovery rates for on- and off-frequency maskers, in contrast with the data for a longer masker duration (150 ms).
(3) For the five listeners with sensorineural hearing loss at the probe frequency, no significant differences between recovery rates for on- and off-frequency 150-ms tonal maskers were observed, when the off-frequency masker was presented at a high level (92 dB SPL).
(4) Overall, the findings for NH and HI listeners suggest that different rates of recovery are not simply a result of temporal confusion in the on-frequency masking condition. Instead, the results suggest that a mechanism with a relatively slow time course that is dependent on normal cochlear function may play a role.
(5) The pattern of the results is consistent with the time course and level dependence of two feedback-based mechanisms, the MEMR and the MOCR. In the case of the MOCR, changes in the slope of the compressive input-output function, or in the breakpoint between low-level linear processing and mid-level compression, could account for the changes in forward-masking patterns. Further investigation, involving measurements of the effect of the stimuli used here as maskers on the SFOAE evoked by the probe frequency, is needed to determine if either of the two suggested mechanisms is indeed involved and to distinguish between the two mechanisms.

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[1]A power function defined by $L_s = a(d/10)^{-b}$, where L_s is the signal level at threshold, d is the offset-to-offset masker-signal delay in ms, and a and b were free parameters, was fitted to each recovery function separately, as in Wojtczak and Oxenham, 2009. The value of parameter b determined the slope of the recovery function. Values of b were compared for functions fitted to thresholds for the equivalent on- and off-frequency maskers.

[2]Ratios of b values rather than differences were used for a t-test to make comparisons between conditions because differences depended on the magnitude order of b values for a given condition and could artificially lead to highly significant effects. This is particularly evident when comparing data from NH listeners with the data from the HI listeners, for whom b values were smaller by an order of magnitude. Because recovery functions were not measured for the 150-ms tonal maskers in this study, the b values from our earlier study (Wojtczak and Oxenham, 2009) were used to compare the b ratios for the equivalent on- and off-frequency maskers with those obtained for the 30-ms tonal maskers in the present study.

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