A variant temporal-masking-curve method for inferring peripheral auditory compression[a)]

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Recent studies have suggested that the degree of on-frequency peripheral auditory compression is similar for apical and basal cochlear sites and that compression extends to a wider range of frequencies in apical than in basal sites. These conclusions were drawn from the analysis of the slopes of temporal masking curves (TMCs) on the assumption that forward masking decays at the same rate for all probe and masker frequencies. The aim here was to verify this conclusion using a different assumption. TMCs for normal hearing listeners were measured for probe frequencies (f_P) of 500 and 4000 Hz and for masker frequencies (f_M) of 0.4, 0.55, and 1.0 times the probe frequency. TMCs were measured for probes of 9 and 15 dB sensation level. The assumption was that given a 6 dB increase in probe level, linear cochlear responses to the maskers should lead to a 6 dB vertical shift of the corresponding TMCs, while compressive responses should lead to bigger shifts. Results were consistent with the conclusions from earlier studies. It is argued that this supports the assumptions of the standard TMC method for inferring compression, at least in normal-hearing listeners. © *2008 Acoustical Society of America.* [DOI: 10.1121/1.2835418]

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I. INTRODUCTION

It is now believed that our ability to perceive sounds over a wide range of sound pressure levels (SPLs) is accomplished via a form of compression that takes place in the peripheral auditory system and is almost certainly related to basilar membrane (BM) compression (Bacon *et al.*, 2004). There exist several psychoacoustical methods to estimate the amount of peripheral compression in humans: the growth-of-masking (Oxenham and Plack, 1997), the additivity of masking (Plack *et al.*, 2006), the pulsation threshold (Plack and Oxenham, 2000), and the temporal-masking-curve (TMC) (Nelson *et al.*, 2001) methods are the most significant. Of these, the TMC method of Nelson *et al.* (2001) is perhaps the most accurate because it minimizes off-frequency listening. However, some of its assumptions and the results obtained with this method have been recently questioned (see the following text). This report describes a variant TMC method that is based on different assumptions than the standard method and yet yields similar results.

The method of Nelson *et al.* (2001) consists of measuring the level of a tonal forward masker required to just mask a fixed tonal probe as a function of the time interval between the masker and the probe. A TMC is a graphical representation of the resulting masker levels against the corresponding masker–probe intervals. Because the probe level is fixed, the masker level increases with increasing the masker–probe time interval and hence TMCs have positive slopes. Nelson *et al.* (2001) argued that the slope of any given TMC depends *simultaneously* on two factors: (a) the amount of BM compression affecting the masker at a cochlear place whose characteristic frequency (CF) equals approximately the probe frequency and (b) the rate of decay of the internal (postcochlear) masker effect. [A full justification of these assumptions can be found in Nelson *et al.* (2001)]. By *assuming* that the time course of decay of the postcochlear masker effect is identical for *all* masker frequencies (and levels), the degree of BM compression can be estimated by comparing the slope of a TMC for any masker frequency against the slope of a TMC for a masker that is processed linearly by the BM (usually referred to as the linear reference TMC). Clearly, the validity of the compression estimates obtained with this method depends on (1) the selection of a suitable linear reference TMC and (2) the accuracy of the assumption that the time course of decay of the postcochlear masker effect is the same for all masker frequencies. Note, however, that this method does not require making assumptions about the actual form of the decay function.

The selection of the linear reference TMC has been justified based on physiological evidence. Nelson *et al.* (2001) reasoned that the TMC for a masker frequency approximately an octave below the probe frequency would be a good linear reference because the BM responds linearly to stimuli well below CF (Robles and Ruggero, 2001). Lopez-Poveda *et al.* (2003) pointed out, however, that there is physiological evidence that compression extends to very low frequencies (relative to CF) for apical cochlear sites (Rhode and Cooper, 1996) and proposed using an off-frequency masker (2 kHz) for a *high*-frequency probe (4 kHz) as the linear reference throughout. This suggestion stands on the

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additional (third) assumption that the time course of decay of the postcochlear masker is the same for all *probe* frequencies.

Based on these three assumptions, Lopez-Poveda *et al.* (2003) concluded that the degree of on-CF BM compression is similar across cochlear places with CFs from 500 Hz to 8 kHz, and that BM compression extends to a wider range of frequencies (relative to CF) in apical than in basal cochlear sites. These results have been confirmed independently by other authors using similar (e.g., Plack and Drga, 2003; Nelson and Schroder, 2004) and also different assumptions (e.g., Plack and Drga, 2003).

The assumptions of the TMC method, however, have been recently challenged by the characteristics of TMCs of hearing-impaired listeners. First, off-frequency TMCs at 4 kHz appear on average twice as steep for normal-hearing listeners as for listeners with mild-to-moderate sensorineural hearing loss (Plack *et al.*, 2004; Lopez-Poveda *et al.*, 2005). This suggests that either the postcochlear effect of the masker decays more slowly for hearing impaired listeners *or* that the off-frequency TMCs of normal hearing listeners are subject to some degree of cochlear compression even at 4 kHz. If the latter were true, it might invalidate the "standard" linear reference TMC, as defined by Lopez-Poveda *et al.* (2003). Second, the TMCs of *some* listeners with uniform moderate-to-severe sensorineural hearing loss are steeper for low than for high probe frequencies (Stainsby and Moore, 2006). The lack of measurable distortion-product otoacoustic emissions (DPOAEs) in these listeners was taken as indicative of a passive, thus linear, cochlea. Therefore, the result was interpreted as though the postcochlear masker effect decays more rapidly with time for lower than for higher probe frequencies (Stainsby and Moore, 2006), which undermines the conclusion that the degree of BM compression is similar across cochlear sites (Lopez-Poveda *et al.*, 2003; Plack and Drga, 2003; Nelson and Schroder 2004).

The present study aimed to reassess on- and off-CF compression at 0.5 and 4 kHz in normal-hearing listeners using a variant TMC method that does not require assuming identical time courses of decay across frequencies or a linear reference TMC. The results support the conclusions of earlier studies based on the standard TMC method. The results also suggest that the TMC for a 4 kHz probe and a 2.2 kHz masker may still be subject to compression and hence that those studies that have employed this TMC as a linear reference may have underestimated the degree of compression. It will be argued that the TMC for a 4 kH probe and a 1.6 kHz masker is an appropriate linear reference and that, contrary to what has been suggested by studies in hearing-impaired listeners, the standard TMC method is valid to estimate BM compression in *normal-hearing* listeners, even at 500 Hz, when this linear reference is used.

II. METHODS

A. Rationale and assumptions

The standard TMC method allows for the inference of compression for any given frequency by comparing the slopes of the TMC for that frequency with that of a linear reference TMC. The method proposed here, by contrast, allows estimating compression from two TMCs that are identical except that they are measured with slightly different probes levels. The *assumption* is that given a small increase in probe level (ΔL_P dB), linear cochlear responses to the maskers should lead to a similar increase in masker level for any masker–probe time interval and thus to a ΔL_P-dB vertical shift of the corresponding TMCs, while compressive responses should lead to bigger shifts. For a fixed masker–probe interval, the ratio of the masker-level increment to the probe-level increment provides a direct compression-ratio estimate and its inverse an estimate of the slope of the BM input/output (I/O) function (or the compression exponent). For example, a 24 dB increase in masker level for 6 dB probe-level increase would imply a 4:1 compression ratio or a 0.25 compression exponent. The masker level increases as the masker–probe time interval increases. Therefore, measuring the masker-level increment for different masker-probe intervals allows for the inference of the degree of compression for different masker levels.

This new method has the same advantages as the standard TMC method. As with the standard TMC method, the negative effects of off-frequency listening (O'Loughlin and Moore, 1981) are minimized by using two *low* probe levels (say 9 and 15 dB SL). The two probe levels are similar, low and fixed for each TMC, hence it is also reasonable to assume that the compression estimates correspond to a BM place with a CF approximately equal to the probe frequency. Furthermore, like the standard TMC method, the new method does not require making assumptions about the actual form of the function describing the decay of the postcochlear masker effect. The proposed method, however, has the advantage over the standard method that it circumvents the need for a linear reference TMC or for assuming that the decay function is the same across frequencies. Hence, this new method also allows testing the linearity of the linear reference TMCs used in earlier studies (see the following text).

The proposed method, however, assumes that the BM responds linearly over the range of *probe* levels considered, which is based on the fact that BM responses to CF tones grow linearly at low levels [reviewed by Cooper (2004) and Robles and Ruggero (2001)]. It also assumes that the time course of decay of the postcochlear masker excitation is the same for the two probe levels considered here. This is supported by the fact that it is almost certain that auditory nerve adaptation contributes significantly to forward masking [although it is probably not the only factor; Meddis and O'Mard (2005), Oxenham (2001)] and the time course of recovery of auditory nerve firing from previous stimulation is independent of probe level (Smith, 1977). Failure to meet these assumptions could result in inaccurate compression estimates. These issues are fully discussed in Sec. IV.

B. Stimuli

TMCs were measured for probe frequencies (f_P) of 0.5 and 4.0 kHz, for masker frequencies (f_M) of 0.4, 0.55, and $1.0f_P$, and for probe levels (L_P) of 9 and 15 dB above the

TABLE I. Absolute threshold (in dB SPL) for each probe frequency (f_P) and listener.

	Listener					
f_P (Hz)	S1	S2	S3	S4	S5	S6
500	32.6	42.8	35.8	34.0		
4000	23.8	27.9	24.8		34.4	35.0

listeners' absolute thresholds for the probes (SL). For any given condition (f_P,f_M,L_P), the masker levels required to just detect the probe were measured for increasing masker–probe intervals (defined from masker offset to probe onset) ranging from 2 to 100 ms, with 5 ms interval increments within the range 5–100 ms. The sinusoidal maskers and probes had total durations of 110 and 10 ms, respectively, and were both gated with 5 ms onset/offset raised-cosine ramps.

Stimuli were generated with a Tucker Davis Technologies psychoacoustics workstation (System III) at a sampling rate of 48.8 kHz and 24 bit resolution. All stimuli were played monaurally via the workstation's headphone connections through the same pair of Etymotic ER2 headphones. Listeners sat in a double-walled sound-attenuating room. The SPLs reported in the following are nominal electrical levels.

C. Procedure

Masker levels at threshold were measured with a two-interval, two-alternative forced-choice (2IFC) adaptive tracking procedure with an interstimulus interval of 500 ms. The masker and probe frequencies were fixed in any given block of trials. The probe level was fixed at 9 or 15 dB SL. The initial masker level was typically set 6 dB below the probe level and was varied adaptively using a two-up, one-down rule to obtain the value needed to achieve the 70.7% correct on the psychometric function (Levitt, 1971). The masker level was increased and decreased by 4 dB for the first 2 reversals and by 2 dB thereafter. Fourteen reversals were recorded in each experimental block and the threshold estimate was taken as the mean of the last 12 reversals. The estimate was discarded when the corresponding standard deviation (s.d.) exceeded 6 dB. The estimate was also discarded, and attempted later if possible, when the masker reached the maximum allowed SPL output of the system (104 dB SPL) in two consecutive trials. Three threshold estimates were obtained in this way and their values averaged to obtain a mean threshold. If the corresponding s.d. exceeded 6 dB, a fourth threshold estimate was measured and included in the mean.

For every listener, all TMCs for the 15 dB SL probe were measured before the corresponding TMCs for the 9 dB SL. For every TMC, masker levels were measured for increasing masker–probe time intervals.

D. Listeners

TMCs were measured for six normal-hearing listeners, although not all conditions were attempted for all listeners (see Table I). Prior to measuring TMCs, absolute thresholds were measured for the probe tones using a 2IFC adaptive procedure. Each probe threshold was measured at least three times and the results were averaged (Table I). All listeners had previous experience or were given at least 4 h of training in the forward-masking task.

E. TMC fits

An *ad hoc* function was fitted to the measured TMCs and the fitted masker levels were used instead of the measured masker levels to infer BM I/O functions (see the following text). The details of the fitting procedure are given elsewhere (Lopez-Poveda *et al.*, 2005). The R^2 between the original and the fitted masker levels was typically $\geqslant$0.98.

III. RESULTS

A. TMCs for a 4 kHz probe frequency

The left panels of Fig. 1 illustrate the TMCs for a probe frequency of 4 kHz. Closed and open symbols illustrate the measured TMCs for probe levels of 9 and 15 dB SL, respectively. Different symbol shapes represent TMCs for different masker frequencies: circles, 1.0f_P; squares, 0.55f_P; triangles, 0.4f_P. Lines illustrate function fits to the measured TMCs.

Except for listener S5, the on-frequency TMCs for the 9 dB SL probe (closed circles) show a segment with a shallow slope for short masker–probe intervals followed by a steeper segment at longer intervals. For listener S5, masker level also increased rapidly for masker–probe intervals $\geqslant$35 ms, but the actual values could not be measured because they exceeded the maximum system output. The off-frequency TMCs for the 9 dB SL probe (closed triangles and squares) can be described, by contrast, as single segments with a shallow slope. Based on the fact that the BM responds linearly to frequencies an octave or so below CF (Robles and Ruggero, 2001), the steeper segment of on-frequency TMCs has been interpreted to reflect BM compression (Nelson *et al.*, 2001). In summary, the overall shapes of these TMCs are consistent with those reported in earlier studies (Lopez-Poveda *et al.*, 2003; Nelson *et al.*, 2001; Nelson and Schroder, 2004; Plack and Drga, 2003).

The threshold masker levels required to mask the 15 dB SL probe (open symbols) are consistently higher than those required for the 9 dB SL probe. Following the rationale of the present method, the degree of BM compression may be estimated as the ratio of the masker-level increment to the probe-level increment, and the compression exponent as the inverse of this ratio. The increments in masker level for the 6 dB increment in probe level are shown in the right panels of Fig. 1. Masker-level increments of approximately 6 dB occur for the lowest masker frequency (triangles) only. The level increments for the on-frequency masker (circles) range from 6 to 48 dB and those for the 0.55f_P masker (squares)

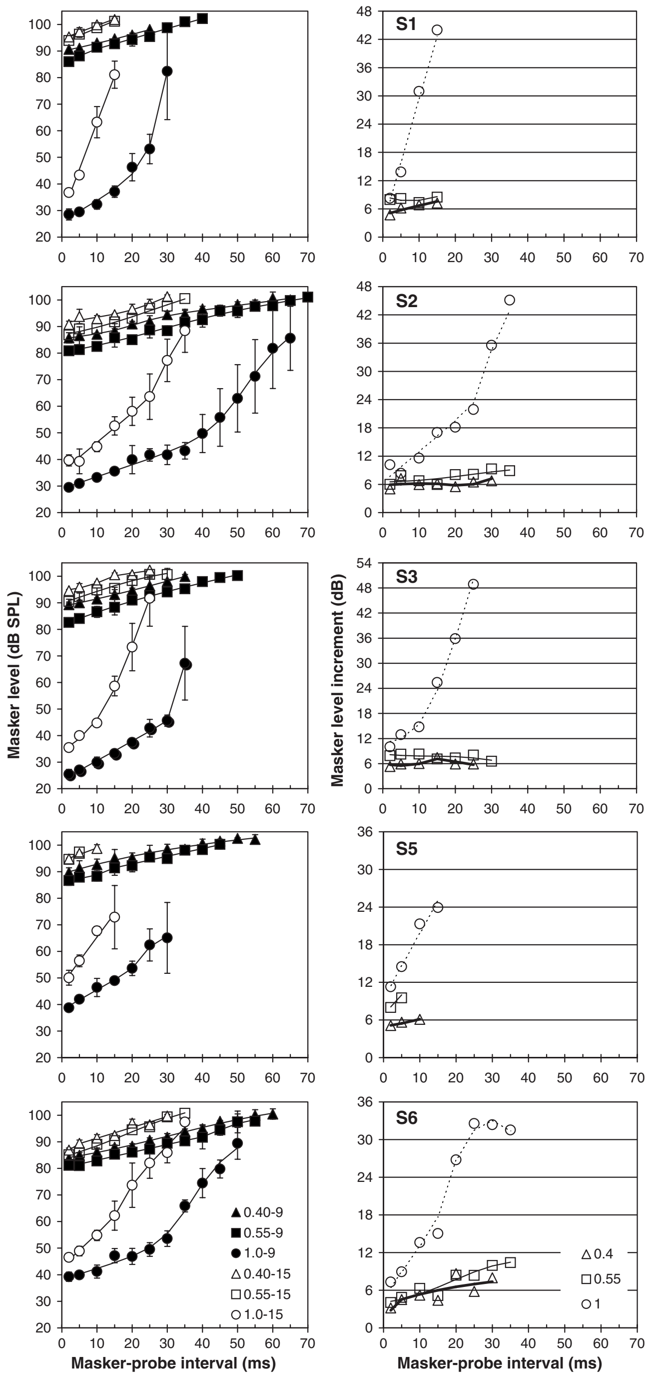

FIG. 1. *Left panels*: TMCs for a probe frequency of 4000 Hz. Each panel illustrates the results for a different listener (as indicated in the top left corner of the right panels). The legend (bottom panel) informs of the masker frequency (relative to CF) followed by the probe level (in dB SL). Symbols illustrate experimental data points. Error bars illustrate 1 s.d. of the mean. Lines illustrate function fits to the measured TMCs. *Right panels*: Corresponding masker-level increments for a 6 dB increment in probe level. Different symbols illustrate the results for different masker frequencies (legend in the bottom panel). Lines illustrate the corresponding differences based on function fits to the measured TMCs.

can be as large 10 dB (S6). This suggests that linear BM responses occur for the $0.4f_P$ masker only, and that the response for the $0.55f_P$ masker is slightly compressed for some listeners (e.g., squares for S6). This also suggests that the compression ratio for on-frequency maskers ranges from 4:1 (S5) to as much as 8:1 (S2 and S3) (see the following text).

It is noteworthy that masker-level increments generally increase with increasing masker–probe interval, except perhaps for the $0.4f_P$ masker (triangles) (see also Sec. IV). Based on the current interpretation of TMCs, this almost certainly reflects that masker-level increments increase with increasing masker level, which in turn increases with increasing masker–probe time interval.

B. TMCs for a 500 Hz probe frequency

Figure 2 illustrates the results for a 500 Hz probe and four listeners. The format is the same as in Fig. 1. Unlike for 4 kHz, the TMCs (left panels) for the 9 dB SL probe (closed circles) do not show two clear segments with different slopes. Instead their slope varies gradually with increasing masker–probe interval from shallow to steep to shallow (S1) or from steep to shallow (S2, S4). Further, the TMCs for the off-frequency maskers (closed squares and triangles) are overall steeper than the corresponding TMCs for the 4 kHz probe (Fig. 1). Overall this pattern is consistent with earlier reports on TMCs for low-frequency probes (Lopez-Poveda *et al.*, 2003; Plack and Drga, 2003; Nelson and Schroder, 2004).

The right panels of Fig. 2 illustrate the masker-level increment for the 6 dB increment in probe level for the different masker frequencies. The results were broadly similar for listeners S1 to S3, but different for S4 and so they will be described separately. For S1–S3, masker-level increments were always ⩾6 dB for all masker frequencies tested. For the on-frequency masker (circles), masker-level increments were as large as 30 dB (S1, S3), which suggests 5:1 compression. Masker-level increments were as large as 18 dB for the $0.55f_P$ masker (squares), which suggests 3:1 compression. Masker-level increments suggests less but still significant (~2:1) compression for the $0.4f_P$ masker (triangles).

The masker-level increments for listener S4 (right-bottom panel of Fig. 2) were between 6 and 12 dB for all masker frequencies and conditions. This suggests less overall BM compression than for the other listeners. This is also supported by the comparatively shallower slope of her corresponding off-frequency TMCs. The reason for this is uncertain, but it is unlikely that it relates to some form of cochlear hearing loss because her absolute thresholds for the probe (Table I) were comparable to those of other listeners (S1, S3).

C. BM I/O functions inferred with the standard and the new method

BM I/O functions were inferred with the standard method by plotting the masker levels for a linear reference TMC against the masker levels for any other TMC, paired according to masker–probe time interval (Nelson *et al.*, 2001). While earlier studies have used the TMCs for masker frequencies of 0.5 or $0.55f_P$ for a 4 kHz probe as linear references (e.g., Lopez-Poveda *et al.*, 2003, 2005; Nelson and Schroder, 2004; Plack *et al.*, 2004; Rosengard *et al.*, 2005), the results shown in the preceding sections (right

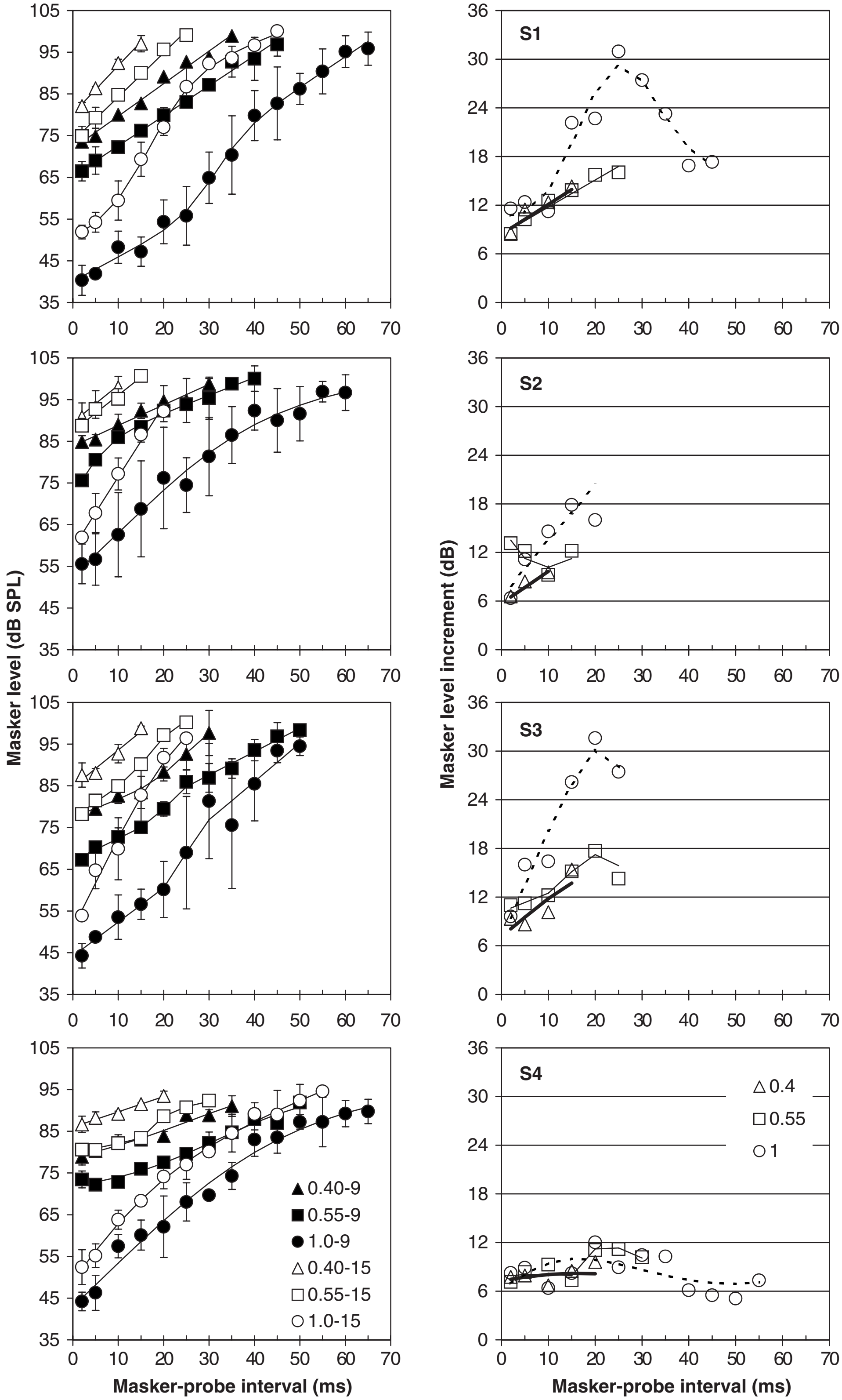

FIG. 2. Same as for Fig. 1 but for a probe frequency of 500 Hz.

panels of Fig. 1) suggest that these maskers may still be subject to compression and that the TMC for a 1600 Hz masker and a 4 kHz probe is a more appropriate linear reference. The closed symbols of Fig. 3 illustrate the resulting BM I/O curves using this linear reference for the three listeners (S1–S3) for whom TMCs were measured for probe frequencies of 500 Hz (left panels) and 4 kHz (right panels). Different symbol shapes illustrate different stimulus frequencies (inset in the middle-left panel). These curves illustrate that significant compression occurs for low, off-frequency tones at 500 Hz, which is consistent with earlier studies (Lopez-Poveda *et al.*, 2003; Plack and Drga, 2003; Nelson and Schroder, 2004). They also illustrate that the functions for the $0.55f_P$ maskers in the right panels of Fig. 3 are

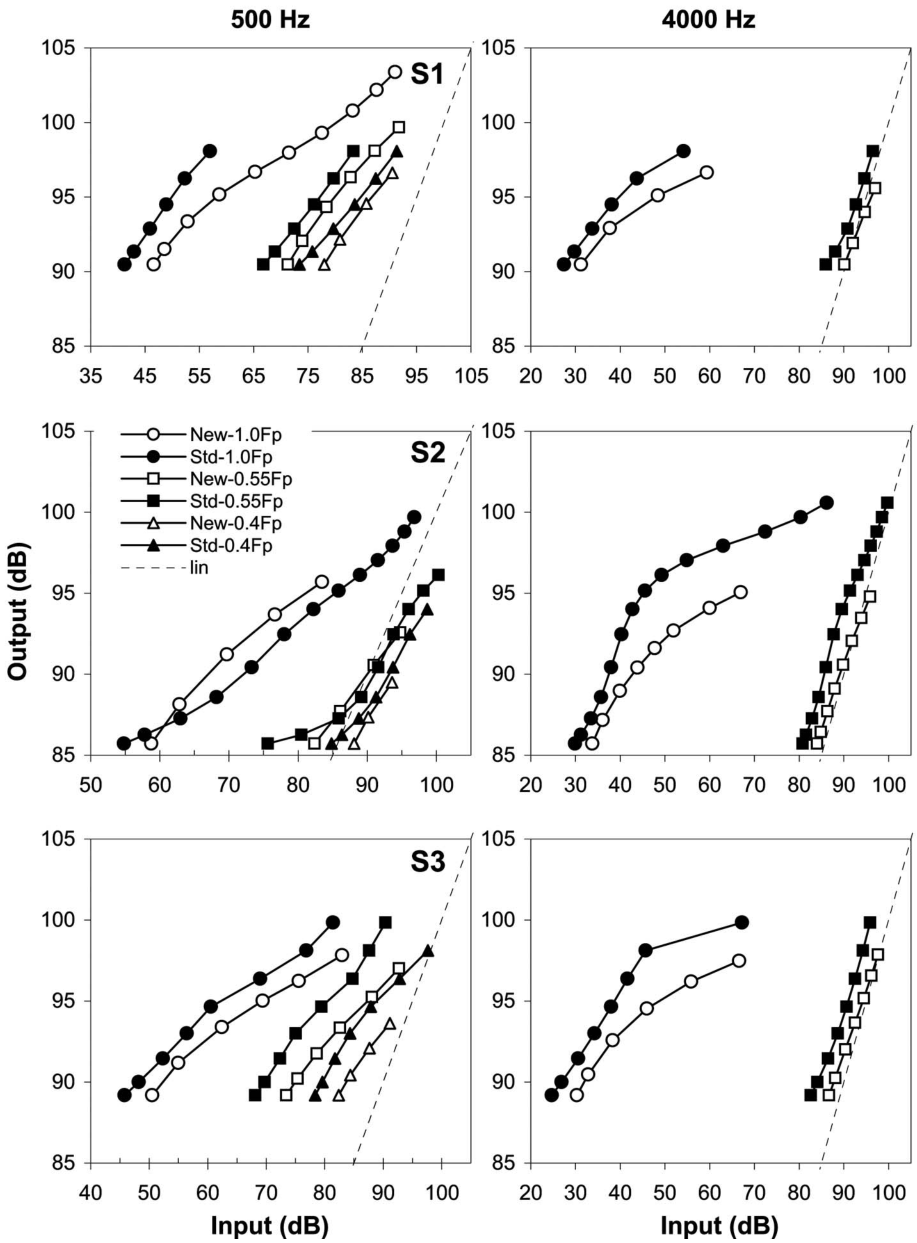

FIG. 3. BM I/O functions at 500 (left panels) and 4000 Hz (right panels) inferred with the standard TMC method (closed symbols) and with the new method (open symbols). Different symbol shapes illustrate the I/O functions for different masker frequencies (as expressed relative to the probe frequency in the inset of the middle-left panel), but the same symbol shapes are used to represent the corresponding functions obtained with the two methods. Note that both sets of curves are based on function fits to the experimental TMCs shown in Figs. 2 and 4. Dashed lines illustrate linear responses with zero gain.

slightly shallower than the dashed lines and hence that slight compression affects the response of the 0.55CF tone at 4 kHz over a narrow range of input levels (see also the following text).

It is also possible and informative to infer BM I/O functions based on the assumptions of the present method. The procedure is described in the Appendix. The resulting I/O curves are illustrated by open symbols in Fig. 3. The shift of these curves with respect to those inferred with the standard TMC method comes from the choice of a constant involved in deriving the new functions, as discussed in the Appendix. With some exceptions (e.g., S2 at 500 Hz), their shapes closely resemble those of the I/O curves inferred with the standard TMC method. Most important, the I/O curves inferred with the new method confirm the two main characteristics of those inferred with the standard TMC method: (1) significant compression affects BM responses to low, off-frequency tones at 500 Hz and (2) slight compression affects the $0.55f_P$ tones at 4 kHz. These coincidences are remarkable considering that the two sets of BM I/O functions were inferred using fundamentally different assumptions.

BM I/O curves inferred with both methods sometimes extend over a different range of input levels (Fig. 3). The actual range of input levels for the I/O curves depends on the number of data points available. For the I/O curves obtained with the new method, fewer data points were available for the TMC measured with the higher-level probe than for the TMC measured with the lower-level probe. As for I/O curves obtained with the standard TMC method, the range of input levels was typically limited by the linear reference TMC, because it contained fewer data points than some of the other TMCs (Figs. 1 and 2). To infer BM I/O functions over a wider range of input levels with the standard TMC method, some researchers (e.g., Lopez-Poveda *et al.*, 2003; Plack *et al.*, 2004) have extrapolated the linear reference TMC to longer masker–probe time intervals using linear regression. This was based on the assumptions that the slope of the linear reference TMC is unaffected by compression and im-

TABLE II. Compression exponent estimates. f_M denotes masker frequency. Two compression estimates are given per listener per condition: The top and bottom values were obtained with the standard and the new TMC methods, respectively. p indicates the probability of the means across listeners being equal for the two methods (two-tailed, paired, Student's t-test).

f_M (Hz)	Method	Listener					Mean ± s.d.	p
		S1	S2	S3	S5	S6		
				4000 Hz				
2400	Standard	0.40	0.57	0.53	0.59	0.58	0.53 ± 0.08	0.12
	New	0.69	0.66	0.73	0.59	0.57	0.65 ± 0.07	
4000	Standard	0.17	0.09	0.08	**0.16**	0.15	0.13 ± 0.04	0.13
	New	0.14	0.14	0.12	**0.24**	0.18	0.16 ± 0.05	
				500 Hz				
200	Standard	0.37	0.37	0.34			0.36 ± 0.02	0.14
	New	0.43	0.62	0.44			0.50 ± 0.11	
275	Standard	0.40	**0.11**	0.32			0.28 ± 0.15	0.44
	New	0.36	**0.44**	0.35			0.38 ± 0.05	
500	Standard	**0.39**	0.18	0.20			0.26 ± 0.12	0.72
	New	**0.20**	0.29	0.19			0.23 ± 0.06	

plies that the postcochlear rate of decay is independent of the masker–probe time interval. However, it will be discussed in the following text that the rate of decay almost certainly varies with time and therefore that linear extrapolation of the linear reference TMC is inaccurate and misleading.

D. Compression-ratio estimates

The main aim of the study was to compare compression estimates for apical (CF ~500 Hz) and basal (CF ~4 kHz) BM regions obtained with the standard TMC method and with the present method. The idea was that because the two methods are based on different assumptions, such comparison allows assessment of the validity of the assumptions of the standard TMC method, particularly that the rate of decay of forward masking is comparable for all masker frequencies and throughout the cochlear CF range from 0.5 to 4 kHz (e.g., Lopez-Poveda *et al.*, 2003). The similarity between the sets of I/O curves inferred with the two methods (Fig. 3) already provides qualitative support for these assumptions. Quantitative support was sought by statistically comparing compression-ratio estimates as inferred with the two methods.

As for the standard TMC method, the compression ratio was calculated as the *minimum* slope of every I/O curve of Fig. 3 (closed symbols) across input levels. The results for each listener and condition are given as compression exponents in Table II (denoted *standard*), where they are compared with the corresponding estimates obtained with the present method (denoted *new*). The latter were obtained as the ratio of the probe-level increment (6 dB) to the *maximum* masker-level increment across masker–probe intervals shown in the right panels of Figs. 1 and 3.

The two methods yield similar compression estimates across listeners and conditions with rare exceptions (denoted in bold in Table II). Indeed, the *mean* compression estimates across listeners are statistically similar for both methods ($p > 0.05$) without exceptions. Furthermore, of the three most significant individual differences (denoted in bold in Table II), two (S5 at 4 kHz and S1 at 500 Hz) occur because the I/O functions obtained with both methods extend over a different range of input levels (as shown for S1 in Fig. 3).

IV. DISCUSSION

A new method for assessing BM compression has been presented that is based on measuring TMCs for two low, slightly different probe levels. Compression was assumed to occur whenever the increase in masker level exceeds the corresponding increase in probe level. Unlike the standard TMC method, this new method does *not* require assuming that the time course of the decay of the postcochlear masker effect be the same across masker and probe frequencies. The compression ratio has been estimated as the ratio of the fixed probe-level increment to the maximum masker-level increment across masker–probe intervals. Compression ratio estimates obtained with the new method were slightly lower but still similar to those obtained with the standard TMC (Table II) method. The measurements obtained with this new method confirm that compression extends to frequencies as low as 0.4CF in the 500 Hz region of the human cochlea. They also suggest that slightly compressive responses (maximum 2:1) occur over a narrow range of levels for frequencies as low as 0.55CF for CF ~4 kHz (right panels of Fig. 1).

A. The time course of decay of the postcochlear masker effect and the assumption that it is independent of probe level

Like the standard TMC method, the present method does not require making assumptions on the actual form of the function describing the time course of the decay of the postcochlear masker effect. For the standard TMC method, it is sufficient to assume that the function is the same across masker frequencies. For the present method, it is sufficient to assume that it is the same for the two probe levels. The latter is supported by the fact that auditory nerve adaptation contributes significantly to forward masking [although probably it is not the only factor; Meddis and O'Mard (2005), Oxenham (2001)] and the poststimulatory rate of recovery of auditory nerve firing appears to be independent of probe level (Smith, 1977).

Some details of the present TMCs, however, undermine this assumption. For example, on-frequency TMCs for the higher-level probe appear sometimes steeper than those for the lower-level probe over the same range of masker levels (e.g., S2 in Figs. 1 and 3). This should not be the case because BM compression must be the same over the same range of levels. One possible explanation for this result is that the masker effect decays faster at short delays and more slowly at long delays. This would agree with earlier modeling studies that suggest that a double exponential recovery process with a fast and a slow time constant gives account of psychophysical (e.g., Oxenham and Moore, 1994; Plack and Oxenham, 1998; Meddis and O'Mard, 2005) and physiological (e.g., Meddis and O'Mard, 2005) forward masking data. This explanation would be consistent also with the fact that some of the linear-reference TMCs become shallower with increasing masker–probe time interval (e.g., closed triangles for S2 and S5 in Fig. 1).

On the other hand, the two on-frequency TMCs of listener S6 in Fig. 1 follow a different trend. They have different slopes for masker levels below around 55 dB SPL and run approximately parallel to each other above that level. Based on the above-presented explanation, one would expect the steeper portion of the on-frequency TMC to be shallower for the lower- than for the higher-level probe because it occurs over longer masker–probe intervals. Furthermore, the slope of the corresponding off-frequency TMCs seems constant across masker–probe time intervals.

Maybe these inconsistencies are only apparent and the effect of a time-dependent decay rate on the TMCs is obscured by its interaction with the effects of BM compression. Or maybe the values of the two time constants and/or their relative contributions to the net decay function vary significantly across listeners. For instance, the TMCs for S6 in Fig. 1 could be consistent with a compression threshold of ~50 dB SPL and a fast time constant of less than 10 ms. This would explain why the slope of the corresponding linear reference TMC hardly changes with increasing masker–probe interval and that the on-frequency TMCs for the two probe levels run parallel to each other. The TMCs for S2, however, would be consistent with a compression threshold of ~45 dB SPL and a fast time constant of ~35 ms because this is the time interval at which the corresponding linear reference TMCs become shallower.

There is, nevertheless, another aspect of the present TMCs that undermine the assumption of identical decay time courses for the two probe levels. For *some* listeners the linear reference TMC is slightly steeper for the higher- than for the lower-level probe (closed versus open triangles in Fig. 1). This subtle difference is more clearly reflected in Fig. 4(a), which shows the increment in the level of the $0.4f_P$ masker for a 6 dB increment in probe level as a function of masker–probe time interval. If the slope of the two linear reference TMCs were identical, then the masker level increment should be approximately equal to 6 dB and constant across masker–probe time intervals. This is the case for some listeners (e.g., S2 or S3). For others (e.g., S1 or S6), however, the increment increases slightly with increasing time interval. This cannot be explained based on a time-dependent decay rate.

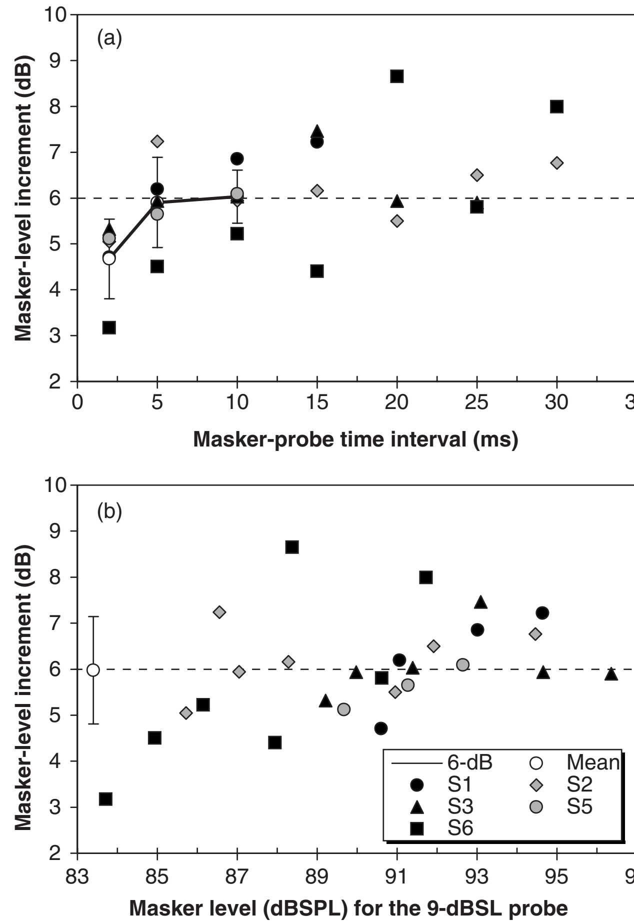

FIG. 4. Increments in the level of a 1600 Hz masker for a 6 dB increment (9–15 dB SL) in the level of a 4000 Hz probe: (a) As a function of masker–probe time interval and (b) as a function of the level for the 9 dB SL masker. Different symbols illustrate the results for different listeners as indicated by the inset in (b). Open circles indicate mean values across the five listeners (a) or across listeners and levels (b). Error bars indicate 1 s.d. The horizontal dashed lines illustrate expected values if the BM response to the probe and the masker were both linear.

Therefore, it is possible that the present TMCs may have been affected idiosyncratically by a factor other than BM compression or the decay rate of the postcochlear masker excitation. The nature of this factor is uncertain. Maybe the TMCs for the 9 dB SL probe were influenced by the difficulty in detecting a very-low level probe. Indeed, we have observed that some untrained listeners find it more difficult to detect very-low level probes for long (>30–40 ms) than for short intervals. This sometimes led to nonmonotonic TMCs (i.e., masker level first increases and then decreases with increasing masker–probe interval). It was as though for moderate-to-long intervals these listeners had lost the cue as to when the probe would occur. The difficulty disappeared when the probe level was raised by a few decibels. It cannot be ruled out that this (or a related factor) may have affected the present on- and off-frequency TMCs, particularly those measured with the 9 dB SL probe. This might explain why the linear-reference TMCs are sometimes slightly shallower for the lower- than for the higher-level probe, as discussed earlier. Of course, TMCs may be simultaneously affected by BM compression, by a time-dependent decay rate, and by this factor.

An estimate of the significance of this uncertain factor was obtained by comparing BM I/O functions derived using a common linear reference for the TMCs for the two probe levels. The idea was that a small effect should produce overlapping I/O functions for the two probe levels (after allowing for a constant 6 dB difference in output level). The TMC for the 1600 Hz masker and the 9 dB SL probe was used as the common linear reference because it generally contained more data points than the corresponding TMC for the 15 dB SL probe. There resulting I/O functions (not shown) for the two probe levels generally overlapped, but there were subtle differences for some listeners and conditions. Specifically, the compression threshold level appeared to be higher in the I/O curves for the lower-level probe in some cases (S2 at 0.5 and 4 kHz; S1 at 4 kHz; and S3 at 0.5 kHz). In any case, this test showed that *maximum* compression estimates were similar for the two sets of I/O curves and hence that the influence of this factor does not compromise the main conclusions of the present study.

The influence of this confusing factor might be reduced by using a cue indicating when the probe would occur and/or by raising the level of the lower-level probe. The latter would also bring the level of the two probes closer, which would minimize factors related to probe-level differences. Unfortunately, using higher probe levels would make it more difficult to measure the linear portion of BM I/O functions that may occur at low levels.

B. BM linearity near threshold

The new method rests on the assumption that for all CFs the BM response to CF tones is linear over the range of probe levels considered. Direct BM responses in lower mammals suggest that this is a reasonable assumption provided that the probe levels are low [evidence reviewed by Cooper (2004), Fig. 2; and Robles and Ruggero (2001), p. 1308], as the present method requires. The assumption is also supported by physiological evidence in humans (Gorga *et al.*, 2007). Psychophysical evidence is, however, confusing. Some studies have suggested that compressive BM responses may occur for *some* listeners even at levels near threshold, but only at *high* CFs (e.g., Fig. 2 of Plack and Oxenham, 2000). Recent studies (Plack and Skeels, 2007), however, suggest that the BM responds linearly near threshold at CFs of 2 and 4 kHz.

If BM compression affected the response to the probe, then the present method would underestimate the degree of BM compression: a 6 dB increment in probe level would produce a smaller increment in internal excitation, which would lead to masker-level increments smaller than would be required had the probe been processed linearly. Incidentally, it is possible to identify instances where this assumption does not hold at *high* CFs considering that linear BM responses occur for sufficiently low stimulus frequencies (relative to CF). Indeed, if compression affected the probe response, a 6 dB increase in probe level should lead to increases in the level of the $0.4f_P$ masker smaller than 6 dB for all masker–probe time intervals (or masker levels). This, however, was rarely observed in the present data (Fig. 4). Except, perhaps, for listener S6, the level increments for the $0.4f_P$ masker at 4 kHz were on average ~6 dB (Fig. 4). Furthermore, on-frequency TMCs at 4 kHz for the 9 dB SL probe show a shallow segment for short masker–probe time intervals over which the rate of growth of masker level with increasing masker–probe delay is approximately similar to that of the $0.4f_P$ masker (Fig. 1). Since the BM response to the latter is likely linear, this supports the assumption that on-frequency BM responses near threshold must also be linear. In any case, the risk of failing to meet this assumption may be minimized by considering probe levels lower and closer than the ones considered here.

C. Implications of the results

Previous studies have shown that the slopes of off-frequency TMCs (2200 Hz) for hearing-impaired listeners at 4 kHz are approximately half of those for normal-hearing listeners (Plack *et al.*, 2004; see also Fig. 3B of Lopez-Poveda *et al.*, 2005). It has been suggested that this may be interpreted as evidence that the internal effect of the masker decays more slowly at high levels *or* that the 2200 Hz maskers may be compressed (by approximately 2:1) in normal-hearing (but not in hearing-impaired) listeners even at CF ~4 kHz (Plack *et al.*, 2004). The above-presented evidence supports the latter. First, it has been shown with two different methods that compression is likely to affect the response of a 2200 Hz tone at 4 kHz (Fig. 3) and the degree of compression approximately matches 2:1 (Table II). Second, if the rate of decay were slower for higher masker levels, then the masker-level increment for a fixed probe-level increment should be gradually smaller with increasing masker level but this was not the case, as shown in Fig. 4(b). If anything, the opposite was true. An alternative explanation for off-frequency TMCs being shallower for hearing-impaired than for normal-hearing listeners is that age, and not the hearing loss *per se*, seems to reduce the rate of decay of forward masking (Gifford and Bacon, 2005). On the other hand, a similar difference in slope has been reported between off-frequency TMCs measured in the two ears of a 24-year-old listener with unilateral hearing loss (Fig. 3 in Lopez-Poveda *et al.*, 2005).

Several studies have considered the TMC for a probe frequency of 4 kHz and a masker frequency of 2200 Hz ($f_M=0.55f_P$) or higher as the linear reference TMC (Plack and Drga, 2003; Rosengard *et al.*, 2005; Nelson and Schroder, 2004). The data in Table II [and Fig. 1(b)] suggest that the slope of this TMC may be affected by approximately 2:1 compression and thus that it may be inappropriate to use this TMC as the linear reference. Therefore, it is likely that those studies have underestimated the degree of BM compression. The present data also suggest that the TMC for the $0.4f_P$ would be a better linear reference TMC.

The new method provides compression estimates that are similar to those obtained with the standard TMC method when a linear reference of $0.4f_P$ is used (Fig. 3 and Table II). Given that the two methods are based on fundamentally different assumptions, this provides indirect support for the postulates of the standard TMC method; particularly, for the assumption that the rate of decay of forward masking is similar across probe frequencies (Lopez-Poveda *et al.*, 2003, 2005; Plack and Drga, 2003; Nelson and Schroder, 2004; Rosengard *et al.*, 2005). This, however, appears inconsistent with the conclusion of Stainsby and Moore (2005) that "the rate of decay of forward masking is not the same for all probe frequencies" (or equivalently, for all cochlear sites). The reason for the discrepancy is uncertain, but it may relate to the following.

The conclusion of Stainsby and Moore (2005) was based on TMCs of hearing-impaired rather than normal-hearing listeners. Stainsby and Moore regarded the absence (or the presence of small values) of *measurable* DPOAEs in their listeners as indicative of purely passive and thus linear cochlear responses. It is conceivable, however, that this was not the case. It is technically difficult to measure DPOAEs below 1000 Hz even in normal-hearing listeners because of ambient noise (e.g., Gorga *et al.*, 2007). Therefore, the lack of *measurable* DPOAEs in their hearing-impaired listeners did not necessarily imply that their listeners lacked them or that their cochlea responded linearly. In fact, Stainsby and Moore acknowledged that some of their listeners actually showed some small DPOAEs at some frequencies. This could also explain that their conclusion held for two of their three listeners only.

D. On the merits of different methods for inferring BM compression

Both the present and the standard TMC methods allow inferring BM I/O functions and peripheral auditory compression in normal-hearing listeners and yield similar results (Fig. 3). The present method, however, may be advantageous to infer BM I/O functions in instances when it is not possible to obtain a reliable linear reference TMC. This can happen, for instance, for some (hearing-impaired) listeners for whom the levels of the desired linear reference commonly exceed the maximum system output level.

V. CONCLUSIONS

(1) It is possible to infer BM I/O functions and peripheral auditory compression by measuring corresponding TMCs for two, slightly different probe levels. The compression exponent may be estimated directly as the ratio of the increase in probe level to the *maximum* increase in masker level.

(2) Strong on-frequency compression occurs both at 500 Hz and 4 kHz. The average compression exponents estimated with the new method were 0.23 and 0.16, respectively. The new method confirms that compression extends to a wider frequency range at 500 Hz than at 4 kHz.

(3) At CF ~4 kHz, BM responses to 0.55CF tones show approximately 2:1 compression. Therefore, previous studies that have used the TMC for a masker frequency of 2200 Hz and a probe frequency of 4 kHz as a linear reference may have underestimated the degree of compression. BM responses to 0.4CF tones are linear at 4 kHz and therefore the TMC for a $0.4f_P$ masker is a more appropriate linear reference TMC than that for a $0.55f_P$.

(4) The present method sometimes underestimates the degree of compression but its results generally match those obtained with the standard TMC method. Because the two methods are based on fundamentally different assumptions, this provides circumstantial support to the assumptions of the standard TMC method; particularly that the postcochlear rate of decay of the internal masker excitation is comparable for cochlear sites with CFs of 500 Hz and 4 kHz.

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APPENDIX: INFERRING BM I/O FUNCTIONS FROM TMCS FOR TWO PROBE LEVELS

It is possible to infer *approximate* BM I/O functions for any CF and stimulus frequency from a pair of TMCs measured with two slightly different probe levels. The procedure is as follows. Let m_1 be the ratio of the (fixed) probe-level increment (ΔL_P) to the (measured) masker-level increment for a given masker–probe time interval, Δt_1:

$$m_1 = \frac{\Delta L_p}{L'_{M1} - L_{M1}}, \qquad \text{(A1)}$$

where L_{M1} and L'_{M1} denote the measured masker levels for the lower- and the higher-level probes, respectively, for the masker–probe interval in question. m_1 may be regarded *approximately* as the *local* slope of the BM I/O function affecting the masker for an intermediate masker (input) level between L_{M1} and L'_{M1}; that is for input level $x_1=(L_{M1}+L'_{M1})/2$. By estimating m for all possible masker–probe intervals, one obtains an approximate function describing the slope of the BM I/O curve against the input masker level, $m(x)$. Then, the I/O function, $y=f(x)$, may be obtained by integrating the slope function, $m(x)$, numerically as follows:

$$y_1 = C,$$

$$y_{n+1} = m_n(x_{n+1} - x_n) + y_n \quad \text{for } n > 1, \qquad \text{(A2)}$$

where $x_{n+1} > x_n$ and C is an undetermined constant. C determines the absolute output values (i.e., it shifts the I/O vertically) but the relative output range and the slope of the resulting I/O function are independent of this constant. Thus, it may be set to any suitable value.

Example I/O curves inferred with this method are shown in Fig. 3, where they are compared with corresponding I/O functions inferred with the standard TMC method. In this case, C was set so that the curves for the two methods start at the same ordinate value. The new method requires pairs of masker levels for the lower- and the higher-level probes, and it may be sometimes impossible to measure the latter for the longer masker–probe time intervals (Figs. 1 and 3). This sometimes limits the range of input levels of the I/O curves estimated with the present method. One advantage of the present method over the standard TMC method is that it does *not* require assuming that the time course of the decay is similar across masker and probe frequencies.

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