EFFECT OF BASILAR MEMBRANE COMPRESSION ON MASKING PERIOD PATTERNS (MPPS)

A paper presented to the 138th Acoustical Society of America
Columbus, Ohio
November 2, 1999

Magdalena Wojtczak,

Anna C. Schroder,

Ying-Yee Kong,

and

David A. Nelson

Clinical Psychoacoustics Laboratory
Department of Otolaryngology
University of Minnesota

Send correspondence to:
Magdalena Wojtczak, Ph.D.
396 UMHC Rm 8-323
516 Delaware St. S.E.
Minneapolis, MN 55455
Phone: (612) 626-4693
Fax: (612) 625-2101
Email: Magdalena.Wojtczak-1@tc.umn.edu

ABSTRACT

MPPs were measured in listeners with normal and impaired hearing using tonal 4-Hz SAM maskers and short tonal probes with frequencies that were either identical to or higher than the carrier frequency of the masker. The probe frequencies were 500, 1200, and 3000 Hz for on-frequency masking, and 1200, 2400, and 6000 Hz for off-frequency masking. In normal-hearing listeners MPPs measured with off-frequency probes had valleys that were much longer and deeper than valleys observed with on-frequency probes. A similar result was observed in hearing-impaired listeners in the frequency region of mild hearing losses, where significant residual compression was presumably operating. However, in the frequency region with substantial hearing loss where compression is substantially reduced or absent, MPPs measured with the on- and off-frequency probes were very similar. A model consisting of peripheral filtering, compressive nonlinearity, and a sliding temporal window was used in an attempt to predict the data and to estimate the compression index. The results suggest that the similarity of on- and off-frequency temporal resolution in hearing-impaired listeners may be due in part to the lack of the compressive nonlinearity that is evident at the level of the basilar membrane in normal-hearing listeners. [Work supported by NIH-NIDCD grant DC00149 and the Lion's 5M International Hearing Foundation.]

INTRODUCTION

Masking period patterns measured with maskers modulated at different rates provide information about temporal processing in the auditory system. A masking period pattern is obtained when detection of a short probe is measured as a function of the temporal position of the probe within a modulation cycle of a masker. As the modulation rate of a masker increases, detection of the probe in a valley of the masker envelope becomes more difficult and a higher probe level is necessary to reach the threshold. Detection of the probe presented during the peak remains unchanged. Thus, the difference between the detection threshold of the probe measured at a peak and the detection threshold measured at a valley decreases with increasing modulation rate of the masker, reflecting deteriorated temporal resolution. Fig. 1 shows a probe presented during a valley of a masker modulated at two different rates (upper panels). Lower panels of the figure show hypothetical masking period patterns measured over two modulation cycles of the masker shown above them. Higher modulation rate produces a masking pattern with shallower valleys.

Zwicker (1976), Nelson and Swain (1996) and recently Gregan et al. (1998) measured masking period patterns using masker frequencies that were equal to the frequency of a probe (on-frequency maskers) and masker frequencies that were lower than the frequency of a probe (off-frequency maskers). Their data indicated that for a given modulation rate, and a given modulation depth of the masker, deeper valleys and larger peak-valley differences are observed in masking period patterns measured with off-frequency maskers than in masking period patterns measured with on-frequency maskers. Based on this observation they concluded that temporal resolution is better in the upper accessory excitation than it is in the main excitation.

The aim of the present study was to demonstrate that the "better temporal resolution" observed with a lower-frequency (off-frequency) masker reflects compressive nonlinearity of auditory processing. A model, in which a linear response to the low-frequency masker at the probe-frequency place and a compressed response to the on-frequency masker and the probe were assumed, was used to predict masking period patterns measured with an on- and off-frequency masker. The same temporal window was used in both on- and off-frequency masking situations.

EXPERIMENT

Masking period patterns were measured in normal hearing listeners. In a 3AFC task, listeners were asked to detect a short probe in the presence of a longer modulated masker. The probe was a 6-kHz tone burst presented for a duration of 8 ms, including 2-ms raised-cosine ramps. The temporal position of the probe within a cycle of the masker envelope was varied across blocks of trials. Carrier frequencies of 3 kHz for the off-frequency masker and 6 kHz for the on-frequency masker were used in the experiment. The masker was presented for 500 ms and was 100%-modulated at a rate of 4 Hz. Masking period patterns were measured using four levels of the masker: 65, 75, 85 and 90 dB. Not every listener was available for all conditions.

RESULTS

Masking period patterns measured with a 3-kHz masker and a 6-kHz probe are shown in Fig. 2. Different panels contain data collected at different masker levels, as indicated in each panel. As shown in the figure, masking patterns observed with the off-frequency masker have wide and deep clearly defined valleys. For low masker levels the thresholds are limited by the absolute threshold of the probe. For higher masker levels the difference between the threshold measured at the peak and at the valley of the modulated masker is larger than it is with an on-frequency masker, as shown by the data presented in Fig. 3.

Masking period patterns measured with the 6-kHz (on-frequency) masker have very narrow valleys and the peak-to-valley differences are generally small compared with the differences shown for the off-frequency masker. Narrow and shallow valleys of the masking period patterns suggest that temporal processing is deteriorated when the masker and the probe have the same frequencies compared with the case where the masker has a much lower frequency than the probe. The same general result was shown by Zwicker (1976), Nelson ands Swain (1996) and Gregan et al. (1998), although the shapes of the MPPs are defined in somewhat greater detail here.

PREDICTIONS

A model proposed by Oxenham and Moore (1994) was used to predict the measured masking period patterns. The model consisted of peripheral filtering followed by half-wave rectification and compression, which were in turn followed by a temporal window, and a decision device. A temporal window proposed by Moore et al. (1988), each side of which was defined by two ROEX functions, was used to simulate temporal processing. To apply the model to the situation where the masker and the signal have different frequencies and overlap in time, some assumptions needed to be made. Basilar-membrane mechanical data (Ruggero, 1992; Ruggero et al., 1997) and psychophysical data of Oxenham and Plack (1997) indicate that when the masker frequency f_m and the probe frequency f_{pr} are equal, the response to the two stimuli presented simultaneously can be written as

$$\boldsymbol{R}_{m+pr} = \boldsymbol{a} \cdot (\boldsymbol{X}_m + \boldsymbol{X}_{pr})^{\boldsymbol{p}},$$

where X_m+X_{pr} is the half-wave rectified sum of the masker (x_m) and the probe (x_{pr}), and p is the compression exponent for the probe and the on-frequency masker. The response to the masker alone is

$$\boldsymbol{R}_m = \boldsymbol{a} \cdot \boldsymbol{X}_m{}^{\boldsymbol{p}}.$$

The model assumes that the probe is detected in the presence of the masker when the response to the masker plus probe, at the output of the temporal window, exceeds the response to the masker alone at the output of the temporal window by some constant amount in dB (with criterion K). This can be written as

$$20 \cdot \log \frac{\boldsymbol{TW}\{(\boldsymbol{X}_m + \boldsymbol{X}_{pr})^{\boldsymbol{p}}\}}{\boldsymbol{TW}\{\boldsymbol{X}_m{}^{\boldsymbol{p}}\}} = \boldsymbol{K}, \qquad (1)$$

where $TW\{X\}$ denotes a stimulus X at the output of the temporal window.

When the frequency of the masker is lower than the frequency of the probe ($f_m<f_{pr}$), the response to the masker at the probe frequency place can be expressed as

$$\boldsymbol{R_{mp}} = \boldsymbol{b} \cdot \boldsymbol{X_m}^{\boldsymbol{q}}, \tag{2}$$

where q is the exponent characterizing the growth of the response to the masker at the probe frequency place. Because the frequency of the masker was much lower than the frequency of the probe, q was assumed to be equal 1 in the calculations of the predicted masking period patterns. It was further assumed that the same response (R_{mp}) could be produced by a signal (x_s), whose frequency is the same as the frequency of the probe ($f_s=f_{pr}$), and therefore the signal is subject to the same compression as the probe. For such a signal

$$\boldsymbol{R_{mp}} = \boldsymbol{a} \cdot \boldsymbol{X_s}^{\boldsymbol{p}}. \tag{3}$$

From Eqs.(2) and (3), it is possible to find the amplitude of such a signal and express it in terms of the masker

$$\boldsymbol{X_s} = \left(\frac{\boldsymbol{b}}{\boldsymbol{a}}\right)^{1/\boldsymbol{p}} \cdot \boldsymbol{X_m}^{\boldsymbol{q/p}}. \tag{4}$$

The probe will be detected in the presence of signal x_s, when the response to both stimuli exceeds the criterion K. Using Eq.(1) for the criterion, substituting Eq.(4) for X_s and setting C=b/a produces the following formula for the criterion:

$$20 \cdot \log \frac{\boldsymbol{TW}\{(\boldsymbol{C}^{1/\boldsymbol{p}} \cdot \boldsymbol{X_m}^{\boldsymbol{q/p}} + \boldsymbol{X_{pr}})^{\boldsymbol{p}}\}}{\boldsymbol{TW}\{(\boldsymbol{C}^{1/\boldsymbol{p}} \cdot \boldsymbol{X_m}^{\boldsymbol{q/p}})^{\boldsymbol{p}}\}} = \boldsymbol{K}. \tag{5}$$

The probe was detected when its amplitude x_{pr} reached a value for which the criterion K was fulfilled. This approach is very similar to the approach represented by the model proposed by Goldstein (1990).

For each listener, only one condition (the off-frequency masker presented at the highest level at which a given listener was tested) was simulated using five free parameters, four parameters of the temporal window and the compression exponent p. The parameters of the temporal window were then kept the same for all the remaining conditions. All the remaining off-frequency simulations were run with two free parameters (the constant C and the compression exponent p), and the on-frequency simulations were run with one free parameter (the compression exponent p). One of the standard Matlab optimization procedures (by Nelder and Mead) was used to minimize the sum of the squared deviations between the data and the predictions.

Fig. 4 shows the data (symbols) and the predictions (solid lines) for the 3-kHz masker. Each panel shows the data and the predictions for a different subject. The agreement between the data and the predictions is very good. However the predictions were not as accurate for the on-frequency masker, as is shown for one listener in Fig. 5. The greatest discrepancy between the predictions and the data was observed near the bottom of the valley. The compression exponents resulting from the on-frequency simulations were also higher than could be expected based on the results for the off-frequency simulations and higher than the exponents reported previously for cochlear compression. Because no highpass noise was used in the experiment to prevent off-frequency listening, it is likely that the listeners detected the probe through an auditory channel tuned to a higher frequency region. This problem was not taken into consideration by the model. Such off-frequency listening would most likely affect thresholds near the peak significantly more than it would affect thresholds near the valley. Therefore, simulations for the on-frequency masker were rerun with the sum of the squared deviations between the data and the predictions computed for all the data points except four points near each peak of the masking period patterns. Those simulations led to the predictions shown in Fig. 6. There is much better agreement between the predictions and the data within the valley of each masking period pattern, but the discrepancy between the data and the predictions increases when the probe is moved closer towards each peak of the masking period patterns. Also, the compression exponents resulting from those simulations were more similar to the compression exponents observed with the off-frequency masker.

The parameters of the temporal window and the compression exponents resulting from the simulations were similar to those used by Oxenham and Moore (1994) to fit their combined forward and backward masking data. Table I shows the compression exponents for all levels of the on- and off-frequency maskers used in the experiment and in the simulations. Higher compression exponents were observed for the off-frequency masker presented at 65 dB SPL. This could be expected, because the masker presented at such a low level did not produce much masking at the probe-frequency place, and therefore, the level of the probe at threshold measured and computed at the peak of the modulated masker was very low. For low levels the response to the probe is believed to be nearly linear.

Overall, the model produces very good predictions for the off-frequency masker and reasonably good predictions for the on-frequency masker, suggesting that the difference in the shape of masking period patterns measured with an on- and off-frequency masker is mainly due to the difference in the rate of response growth resulting from the on- and off-frequency stimulation. It is not clear whether the psychophysically observed compression directly reflects compression of the basilar-membrane mechanical response. The compression exponents obtained from the simulations were higher than those reported by Ruggero et al. (1997). However, they agree with compression exponents observed in other psychophysical measurements and simulations (Oxenham and Moore, 1994; Gregan et al., 1998).

ACKNOWLEDGMENTS

This work was supported largely by grant DC00149 from NIDCD. It was also supported in part by the Lion’s 5M International Hearing Foundation.

REFERENCES

Oxenham, A.J. and Plack, C.J. (**1997**). “A behavioral measure of basilar-membrane nonlinearity in listeners with normal and impaired hearing,” J. Acoust. Soc. Am. **101**, 3666-3675.

Ruggero, M.A., Rich, N.C., Recio, A., Narayan, S.S. and Robles, L. (**1997**). “Basilar-membrane responses to tones at the base of the chinchilla cochlea,” J. Acoust. Soc. Am. **101**, 2151-2163.

Table I. Compression exponents obtained from MPP simulations.

Masker Level	Masker Position	YYK	KEK	MXW	PJL
90 dB	On-Frequency	0.54	---	---	---
	Off-Frequency	0.51	---	---	0.64
85 dB	On-Frequency	0.51	0.56	0.57	---
	Off-Frequency	0.55	0.51	0.51	0.53
75 dB	On-Frequency	0.58	0.60	0.60	---
	Off-Frequency	0.47	0.43	0.52	0.53
65 dB	On-Frequency	0.61	0.61	0.63	---
	Off-Frequency	0.94	0.76	0.85	0.80

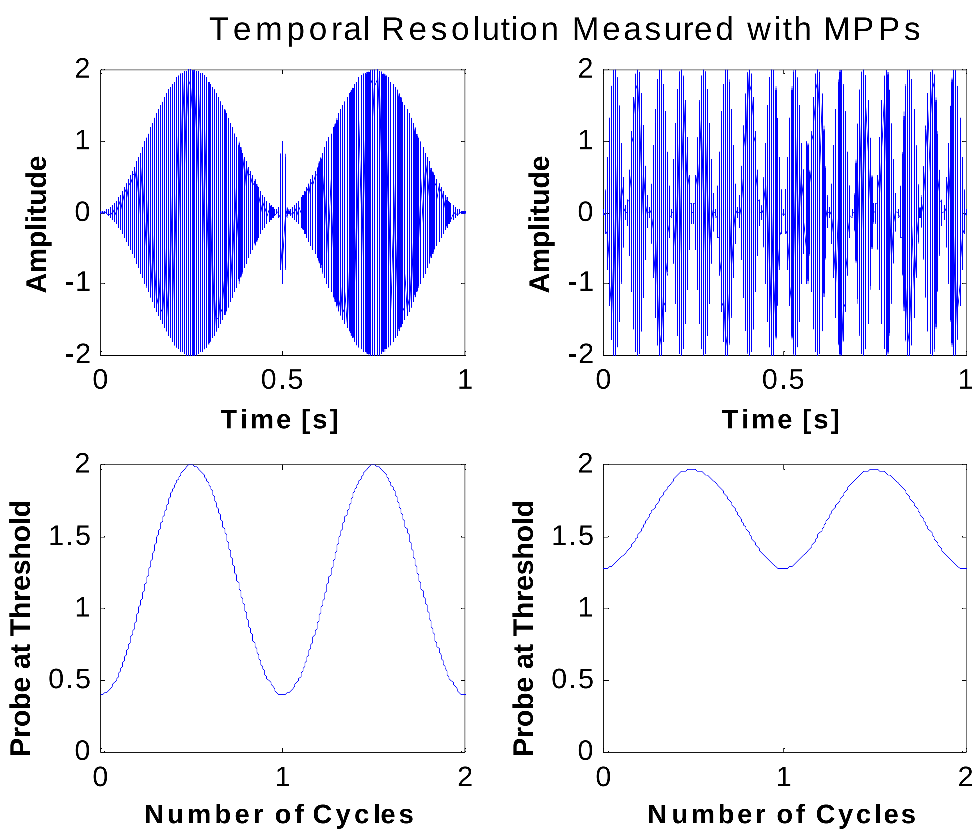

Fig. 1. A masker modulated at two different rates with a signal presented at a valley (upper panels) and hypothetical masking period patterns (lower panels) measured over two cycles of the presented maskers.

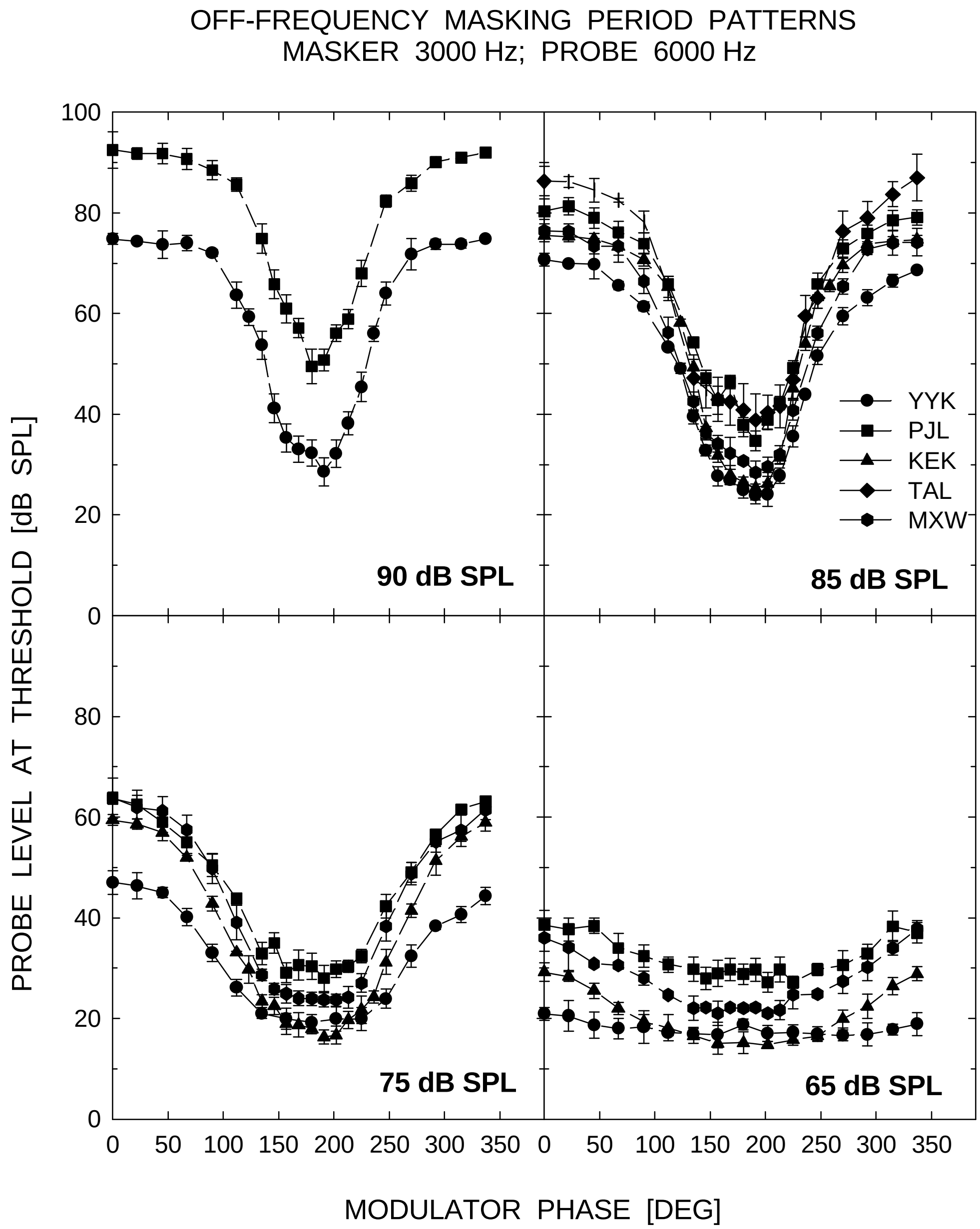

Fig. 2. Masking period patterns measured with a 3-kHz (off-frequency) masker and a 6-kHz probe. Different symbols show the data for different subjects.

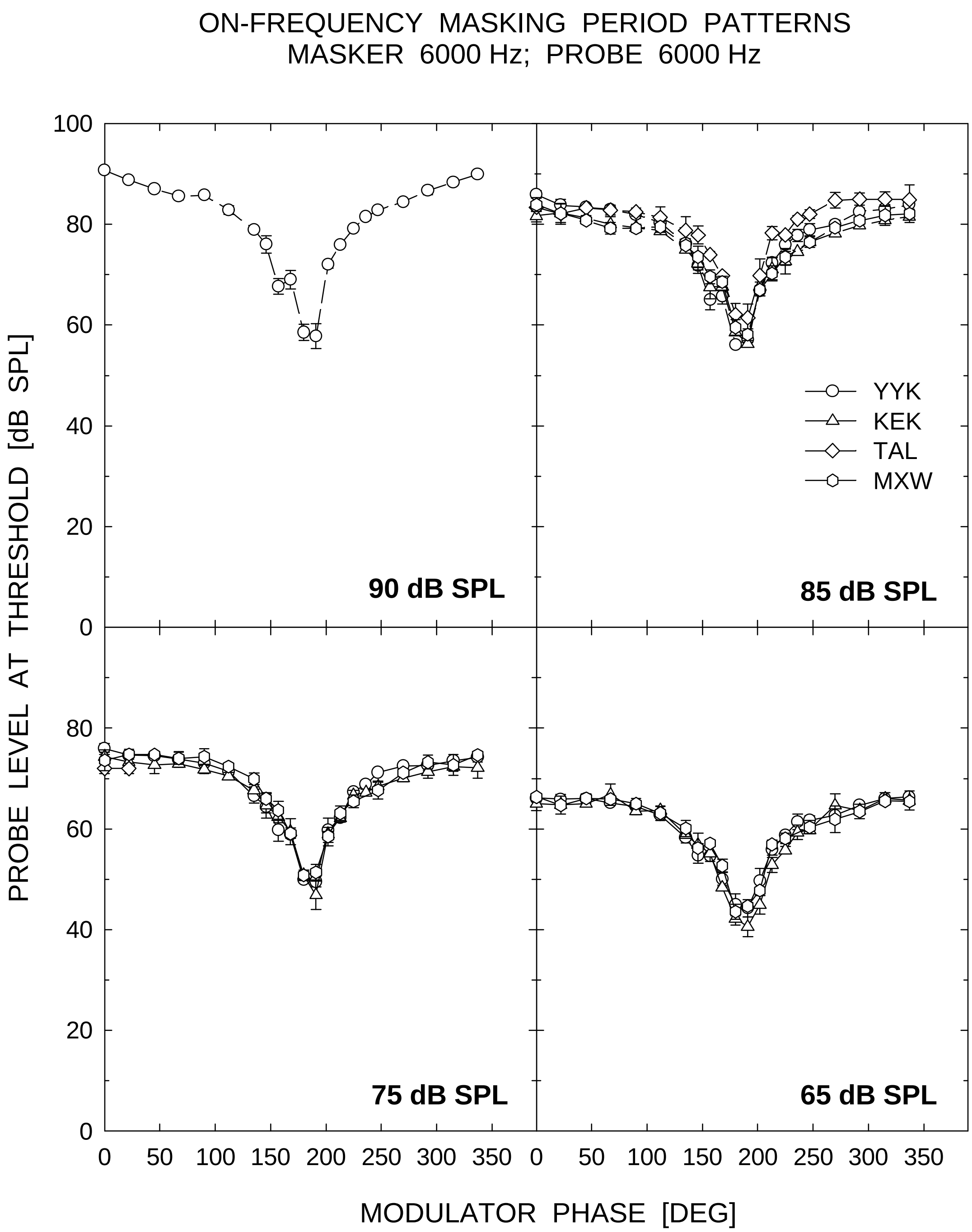

Fig. 3. Masking period patterns measured with a 6-kHz (on-frequency) masker and a 6-kHz probe.

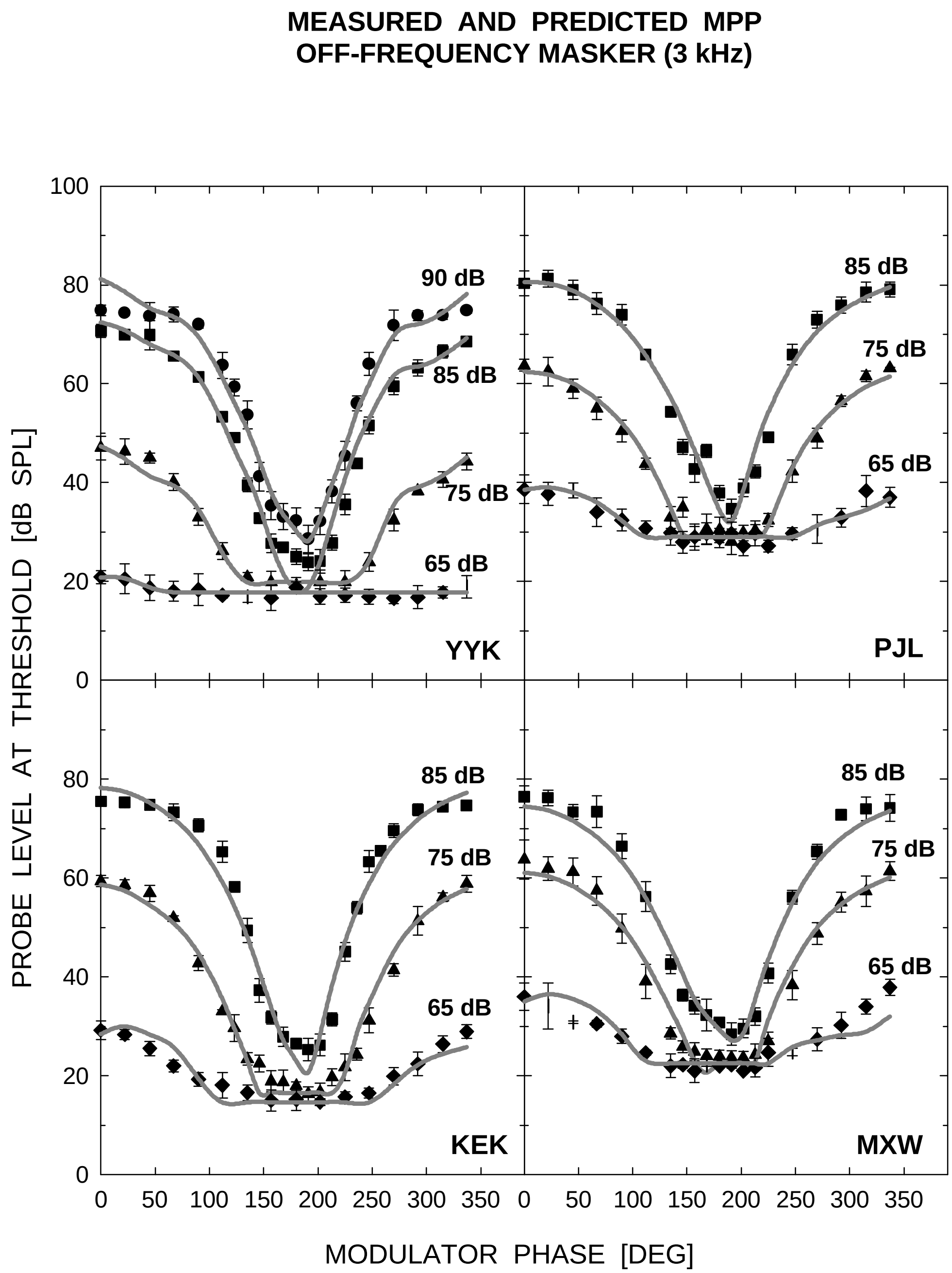

Fig. 4. The data (symbols) and the predictions (solid lines) for the 3-kHz masker and the 6-kHz probe.

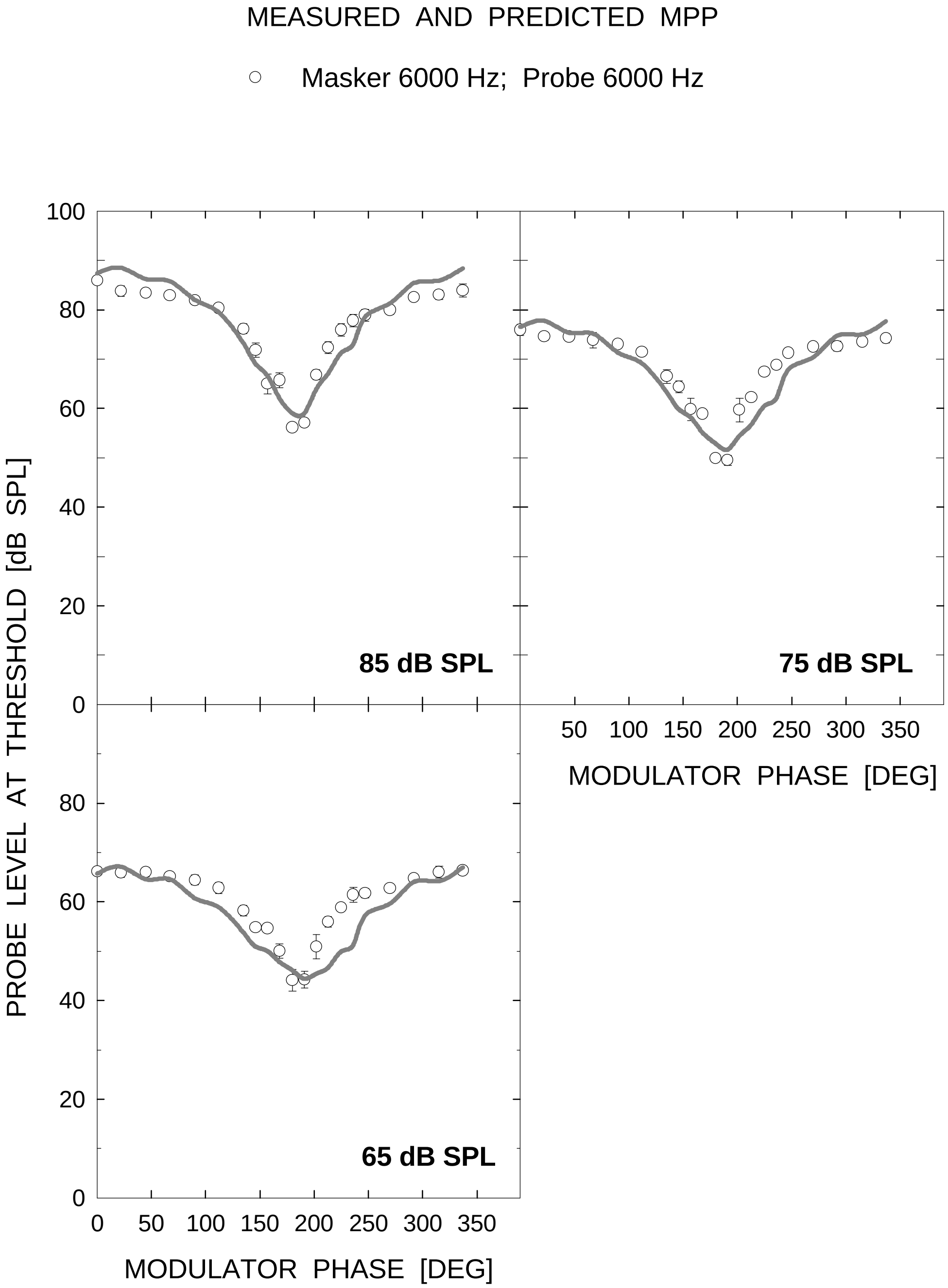

Fig. 5. The data (symbols) and the predictions (solid lines) for the 6-kHz masker and the 6-kHz probe for one listener.

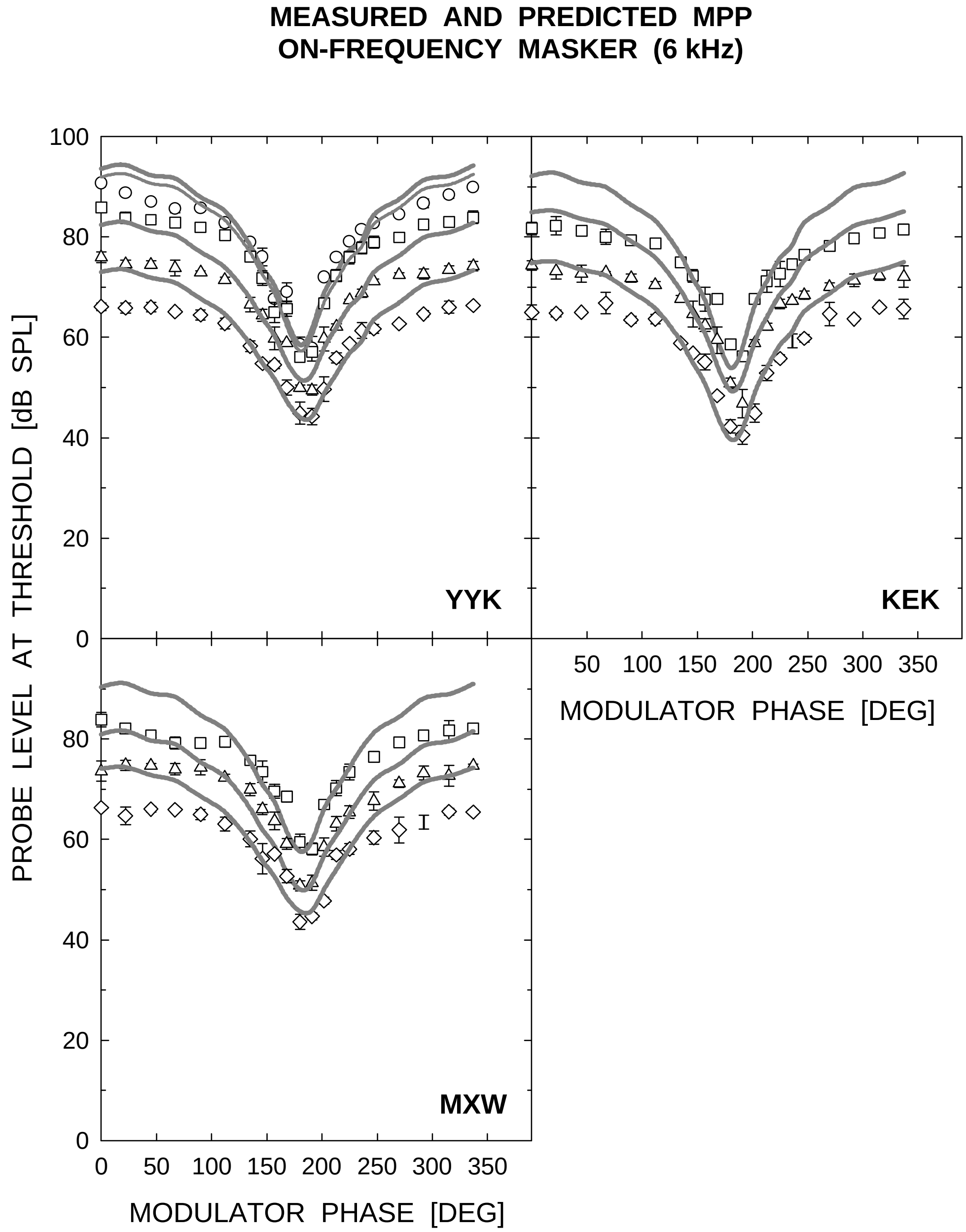

Fig. 6. The data (symbols) and the predictions (solid lines) for the 6-kHz masker and the 6-kHz probe. The predictions were obtained from simulations in which five points near each peak were excluded from the computation of the sum of squared deviations between the data and the predictions.