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Forward masking of amplitude modulation across ears and its tuning in the modulation domain

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Abstract

Frequency selectivity in the amplitude modulation (AM) domain has been demonstrated using both simultaneous AM masking and forward AM masking. This has been explained using the concept of a modulation filter bank (MFB). Here we assessed whether the MFB occurs before or after the point of binaural interaction in the auditory pathway by using forward masking in the AM domain in an ipsilateral condition (masker AM and signal AM applied to the left ear with an unmodulated carrier in the right ear) and a contralateral condition (masker AM applied to the right ear and signal AM applied to the left ear). The carrier frequency was 8 kHz, the signal AM frequency, f_s , was 40 or 80 Hz, and the masker AM frequency ranged from 0.25 to 4 times f_s . Contralateral forward AM masking did occur, but it was smaller than ipsilateral AM masking. Tuning in the AM domain was slightly sharper for ipsilateral than for contralateral masking, perhaps reflecting confusion of the signal and masker AM in the ipsilateral condition when their AM frequencies were the same. The results suggest that there might be an MFB both before and after the point in the auditory pathway where binaural interaction occurs.

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I. INTRODUCTION

It has been proposed that the outputs of the (peripheral) auditory filters are fed to an array of overlapping bandpass filters tuned to different envelope modulation frequencies, based on both physiological data (Schreiner and Langner, 1988) and psychophysical data (Kay, 1982; Martens, 1982; Dau *et al.*, 1997a; 1997b; Ewert and Dau, 2000; Ewert *et al.*, 2002; Verhey *et al.*, 2003). This array of filters is usually called a “modulation filter bank” (MFB), and it is assumed that the MFB mediates at least some aspects of the perception of amplitude modulation (AM). Evidence supporting the existence of an MFB comes from experiments involving the detection of signal AM in the presence of masker AM. These experiments show frequency selectivity in the AM domain (Bacon and Grantham, 1989; Houtgast, 1989; Ewert *et al.*, 2002). Frequency selectivity in the AM domain has also been demonstrated in experiments using AM forward masking, where the signal modulation is presented after the masker modulation (Wojtczak and Viemeister, 2005; Moore *et al.*, 2009; Wojtczak *et al.*, 2011). In addition, listeners have some ability to “hear out” the sinusoidal components of a multi-component modulator, provided that the modulator components are widely spaced in frequency (Sęk and Moore, 2003; 2006). It is not clear whether the MFB is located before or after the level in the auditory system where binaural interaction occurs. The present experiment addressed this issue by assessing whether AM forward masking occurs when the masker AM is presented to one ear and the signal AM is presented to the other ear. This is referred to as contralateral modulation masking. Such masking was found to occur, and its tuning in the modulation domain was quantified and compared with that obtained when the masker and signal AM were presented to the same ear.

Thompson and Dau (2008) suggested two possible ways in which frequency selectivity in the modulation domain could be incorporated into models of binaural processing. In the first way, the MFB is applied to the output of each monaural peripheral auditory filter before the input to the binaural processor. In the second way, the inputs of the peripheral auditory filters are combined in the binaural processor and MFBs are applied both to the output of the binaural processor and (separately) to the output of each monaural peripheral auditory filter (see their figure 9).

Langner and Schreiner (1988) and Schreiner and Langner (1988) provided evidence for neurons tuned to AM frequency in the inferior colliculus, a nucleus that is located in the auditory pathway after the point where binaural interaction first occurs, which is the superior olive (Palmer, 1995). If the neurons found by Langner and Schreiner form the basis for the MFB, then contralateral modulation masking would be expected to occur. On the other hand, neurons tuned to AM frequency have been also been found in the cochlear nucleus, which is located in the auditory pathway before the point where binaural interaction occurs (Palmer, 1995; Joris *et al.*, 2004; Sayles *et al.*, 2013). If the MFB is located before the point of binaural interaction, such that there is a separate MFB for the left and right ears, then little or no contralateral forward masking would be expected to occur, since the output of the MFB on the side receiving the signal AM would be unaffected by the presence of masker AM in the opposite ear.

Psychophysical evidence for binaural interaction in the processing of AM comes from studies showing that human listeners are sensitive to the interaural phase of the envelope of AM sounds for modulation frequencies up to several hundred Hertz. For example, sounds can be lateralized on the basis of interaural envelope delay, for envelope rates up to at least 400 Hz (Henning, 1974; Neutzel and Hafter, 1981; Bernstein and Trahiotis, 2002). However, this might not depend on processing in an MFB, since there is evidence from modulation forward masking that the center frequencies of the modulation filters extend only up to about 100-120 Hz (Moore *et al.*, 2009).

A second line of evidence for binaural interaction in the processing of AM comes from a study of McFadden and Pasanen (1975). They described an analog of binaural beats (Licklider *et al.*, 1950) in the AM domain. A high-frequency two-tone complex was presented to each ear, each complex producing beats with a rate equal to the frequency difference between the two tones. Subjects were required to distinguish between stimuli for which the beat rate was the same at the two ears (e.g., 50 Hz) and for which it was slightly different at the two ears (e.g., 50 Hz in one ear and 51 Hz in the other). When the difference in beat rate was 5 Hz or less, subjects performed well above chance. Subjects reported hearing a fluctuation at a rate corresponding to the difference in beat rate between the two

ears: 1 Hz in the example given above. The effect occurred in the presence of an intense low-pass noise and at low levels, so it cannot be explained by combination tones. Related effects showing binaural interaction in the AM domain have been reported by Grantham (1984), Bernstein and Trahiotis (1996), and Søk *et al.* (2010). However, again it is not clear whether these effects depend on the processing of the AM in a MFB.

In the present study we sought to determine whether contralateral forward masking in the AM domain occurs, and, if so, to quantify its tuning in the AM domain and to compare it with that obtained in monaural forward masking (Wojtczak and Viemeister, 2005; Moore *et al.*, 2009).

II. METHOD

A. Subjects

Three subjects (two male, one female) were recruited from the student population of the University of Cambridge, and paid for their services. All had audiometric thresholds ≤ 15 dB hearing level (HL) for both ears at octave frequencies between 0.25 and 8 kHz, and at 3 and 6 kHz. Their ages ranged from 22 to 37 years (mean age = 28 years; standard deviation, SD = 8 years). All subjects provided informed written consent and the study was approved by the Cambridge Research Ethics committee.

B. Stimuli

Stimuli were generated digitally using a Tucker-Davis-Technologies (TDT, Alachua, FL) system II DD1 digital-to-analog converter with 16-bit resolution and a 50-kHz sampling rate. The stimuli were then attenuated (TDT PA4), passed through a headphone buffer (TDT HB6), and routed to a double-walled sound-attenuating booth, where they were passed through a final manual attenuator (Hatfield 2125, Hatfield, UK). Stimuli were delivered via Sennheiser (Wedemark, Germany) HD580 headphones. A PC controlled the stimulus generation, experimental procedure, and data acquisition.

The stimuli were chosen to be similar to those used by Moore *et al.* (2009). The carrier was an 8-kHz sinusoid with an overall duration of approximately 650 ms (the exact duration

depended on the masker AM frequency, as described below), including 20-ms raised-cosine onset and offset ramps. This high carrier frequency was chosen so that any spectral sidebands produced by the AM would not be resolved in the auditory system (Kohlrausch *et al.*, 2000; Moore and Glasberg, 2001). In each trial, two sequential carrier bursts, separated by a 415-ms silent interval, were presented to both ears at a level 60 dB above the mean absolute threshold for the two ears at 8 kHz. One of the bursts contained the signal AM and the other did not. Figure 1 shows the envelopes of the stimuli for the “signal” interval. In one condition (Fig. 1a), the “absolute threshold” for detecting the signal AM was measured. In this context, “absolute threshold” refers to the threshold for detecting the signal AM in the absence of masker AM. In one randomly chosen interval, both ears received an unmodulated carrier. In the other interval, the right ear received an unmodulated carrier and the left ear received a carrier with a 50-ms-long signal portion whose amplitude was sinusoidally modulated. The signal AM was introduced at least 540 ms after the onset of the carrier, and always started and ended at positive-going zero-crossings. The carrier was unmodulated and at full amplitude for 40 ms after the end of the signal modulation and then the unmodulated carrier was ramped off over 20 ms. The depth of the signal modulation, m , was varied adaptively to determine the threshold, as described in section II.C.

143

144

145 FIG. 1. Example of envelopes of 8-kHz carriers delivered to the left and the right ears for a
 146 signal interval. The 50-ms signal AM (duration t_s) was applied to the carrier presented to the
 147 left ear. In one condition, only the signal AM was present (panel a). In the other conditions,
 148 the signal AM was preceded by masker AM (duration t_m , AM depth $m = 1$), applied either to
 149 the same carrier as the signal AM (panel b; ipsilateral AM masker) or to the carrier presented
 150 to the opposite (*i.e.*, right) ear (panel c; contralateral AM masker). The delay between the end
 151 of the masker AM and the start of the signal AM (duration t_d) was 40 ms. The AM depth of
 152 the signal was adaptively varied (here shown at $m = 0.5$).

153

154 In the second and third conditions (Fig. 1b and 1c), sinusoidal masker AM with

modulation frequency, f_m , was applied to the carrier in one ear in both intervals; this ear was the left for ipsilateral AM masking and the right for contralateral AM masking. No masker AM was applied to the other ear. The masker AM was applied as soon as the carrier was turned on, with a starting phase of 270° , *i.e.*, at its most negative value. The masker AM ended at a positive-going zero crossing (0° phase). The duration of the masker AM was chosen to be close to 500 ms (see t_m in Fig. 1b). To determine its exact duration, the masker AM period in ms, P_m , was divided into 500, and the result rounded to the nearest integer, N . The duration of the masker AM was then computed as:

$$(N \times P_m) + 0.25P_m. \quad (1)$$

The end of the masker AM and the start of the signal AM were always separated by 40 ms (see t_d in Fig. 1b). The depth of the masker AM was $m = 1$ (Fig. 1b, c).

Signal modulation frequencies, f_s , of 40 and 80 Hz were used, resulting in two and four cycles, respectively, of signal AM. For $f_s = 40$ Hz, the approximately half-octave spaced masker AM frequencies, f_m , were 10, 14, 20, 28, 40, 57, 80, 113, and 160 Hz; for $f_s = 80$ Hz, the values of f_m were 20, 28, 40, 57, 80, 113, 160, 226, and 320 Hz.

C. Procedure

First, absolute thresholds for detecting the unmodulated carrier were assessed separately for each ear, using a two-interval, two-alternative forced-choice procedure. In each trial, two intervals, marked by lights on a response box, were presented successively with an inter-stimulus interval of 500 ms. One of the intervals selected at random, contained a 8-kHz pure tone with a duration of 650 ms, including 20-ms raised-cosine rise decay ramps; the other interval was silent. The task was to indicate via a button press which interval contained the tone. Visual feedback as to the correct interval was provided after response entry, and the next trial was initiated automatically after 500 ms. The starting level of the tone was set to be well above the audiometric threshold. A three-down, one-up rule was used to adaptively vary the level to estimate the value necessary for 79.4%-correct detection (Levitt, 1971). The step size started at 4 dB, and was reduced to 2 dB after two reversals and to 1 dB after two more reversals. After 12 reversals, the run was terminated and the mean value of the signal level at

last eight reversal points was taken as the threshold estimate. For each ear, three threshold estimates were obtained and their arithmetic mean was taken as the final estimate of absolute threshold. For the main experiment, the carrier level was set to be 60 dB higher than the mean absolute threshold across the two ears.

Then, AM detection thresholds were measured in both the absence and presence of masker AM. The same adaptive procedure as described above was used to estimate the signal AM depth (expressed as $20\log_{10}m$) required to achieve 79.4% correct. The starting AM depth was set at least 8 dB above the threshold obtained during practice, or, if that yielded an AM depth greater than 0 dB (*i.e.*, an over-modulated stimulus), it was set to 0 dB. If the adaptive procedure called for a modulation depth greater than 0 dB, it was limited to 0 dB. If this occurred more than three times after the fourth reversal, the run was aborted and no estimate was computed. This only happened once for one subject. Also, when the SD of the AM depths at the last eight turn points was ≥ 3 dB, the estimate for that run was discarded, and the run was repeated. For each condition, at least four valid threshold estimates were obtained for each subject. When the SD of the threshold estimates across runs was ≥ 3 dB, an additional estimate was obtained; this was repeated, if necessary, until up to six estimates were measured. Threshold estimates more than 5 dB away from the final mean threshold were regarded as outliers and discarded (1% of all runs). The final estimate was taken as the average across all valid runs.

The ipsilateral and contralateral masker conditions were assessed in separate sessions. Subjects S1 and S3 first completed the contralateral, and then the ipsilateral conditions, whereas S2 did the reverse. Unmasked AM detection thresholds for one signal AM frequency were measured at the beginning of each session, before measuring forward masking thresholds using all masker AM frequencies, in random order. Only one signal AM frequency was used in each session, and usually each masker AM frequency was used twice in each session. At least four sessions were used for each subject.

All subjects were highly trained, with over 30 h of experience with AM forward masking, due to their participation in a previous study using similar stimulus parameters (Moore *et al.*, 2009). However, since only monaural stimuli were used in that study, all

listeners received a further 3-4 h of practice using various signal-masker AM combinations.

III. RESULTS

The results are shown in Fig. 2. Individual and mean AM depths at threshold are plotted in terms of $20\log_{10}m$ (left ordinate) and m expressed as a percentage (right ordinate). Signal AM detection thresholds for 40-Hz and 80-Hz AM in the absence of masker AM are shown by the dashed and continuous horizontal lines, respectively. The average AM threshold was -21 dB (9%) for the 40-Hz signal and -23 dB (7%) for the 80-Hz signal. These thresholds are about 10 dB higher (i.e, worse) than AM thresholds reported in the literature for high-frequency pure-tone carriers (Kohlrausch *et al.*, 2000; Moore and Glasberg, 2001; Füllgrabe and Lorenzi, 2003). This discrepancy and the fact that thresholds in the present study were 2 dB higher for the 40-Hz than for the 80-Hz AM can probably be explained mainly by the small numbers of AM cycles in the signal portion of the stimulus, which was 2 for the 40-Hz AM and 4 for the 80-Hz AM (Sheft and Yost, 1990; Lee and Bacon, 1997). An additional factor is that the signal AM was applied to the carrier in one ear only; the carrier in the other ear was unmodulated. In most previous studies, the signals were diotic, with the signal AM presented to both ears (Kohlrausch *et al.*, 2000).

FIG. 2. Individual and mean results. The signal AM depth at threshold [expressed as $20\log_{10}m$ (left ordinate) and percent (right ordinate)] for 40-Hz (circles) and 80-Hz (squares) signal AM is plotted as a function of the AM frequency (f_m) of the AM masker. Results for the ipsilateral and contralateral conditions are shown by filled and open symbols,

respectively. Larger symbols denote conditions in which the masker and signal had the same AM frequency. A condition in which one threshold run was aborted due to the over-modulation rule is flagged by the light grey symbol; the plotted data point represents the average of completed runs. Error bars in the top three panels indicate ± 1 SD across repeated measures. Error bars in the bottom panel indicate ± 1 SD across subjects. Signal detection thresholds without the forward AM masker are indicated by broken (40-Hz signal) and continuous (80-Hz signal) horizontal lines.

In Fig. 2, the different symbols show forward-masked AM detection thresholds as a function of f_m : circles denote thresholds for the 40-Hz signal, while squares denote those for the 80-Hz signal. Filled symbols indicate the ipsilateral condition, with the masker AM applied to the same carrier as the signal modulation. As found previously for similar stimuli, AM forward masking occurred and it showed tuning in the AM frequency domain, with the highest thresholds occurring for masker AM frequencies close to the signal AM frequency (Wojtczak and Viemeister, 2005; Moore *et al.*, 2009). Open symbols indicate the contralateral condition, with the masker AM applied to the carrier in the opposite ear to that with the signal AM. It is obvious that contralateral AM forward masking did occur, although it was somewhat smaller for the contralateral than for the ipsilateral condition. Averaged across all masker AM frequencies for both signal AM frequencies, the amount of AM masking (masked AM threshold minus absolute AM threshold) was 10.3 dB for the ipsilateral condition and 5.8 dB for the contralateral condition.

To assess the effect of ear of masker presentation (ipsilateral versus contralateral) on AM thresholds and to assess whether frequency selectivity in the AM domain was affected by the signal frequency and by the ear of masker presentation, an analysis of variance (ANOVA) was conducted on the masked AM thresholds with factors ear of presentation, signal AM frequency, and masker AM frequency. For this analysis, the masker AM frequency was divided by the signal AM frequency, i.e., it was expressed relative to the signal AM frequency. The masked AM thresholds sometimes approached the absolute AM detection thresholds for the two lowest and two highest relative masker frequencies. For those cases,

the AM thresholds were probably limited by the approach to the absolute AM detection threshold rather than by the tuning of the MFB. Since our primary interest was to assess whether frequency selectivity in the AM domain was affected by the ear of masker presentation, the results for these relative masker frequencies were excluded from the analysis. When the condition of sphericity was not met, the Huynh-Feldt correction was applied to the degrees of freedom, but the uncorrected degrees of freedom are reported.

There were, as expected, significant effects of ear of presentation [$F(1, 2) = 42.7, p = 0.023$] and of relative masker frequency [$F(4, 8) = 17.7, p = 0.012$]. There was a significant effect of signal AM frequency [$F(1, 2) = 49.3, p = 0.012$], mean masked thresholds being higher for the 40-Hz than for the 80-Hz signal AM frequency. However, the absolute thresholds for AM detection were also higher for 40-Hz than for the 80-Hz signal AM frequency. The mean amount of forward masking (masked threshold minus absolute threshold) was similar for the two AM signal frequencies. The interaction of signal AM frequency and relative masker frequency was significant [$F(4, 8) = 8.57, p = 0.005$], meaning that the pattern of tuning in the AM domain was different for the two AM signal frequencies. The interaction of ear of presentation and relative masker frequency was significant [$F(4, 8) = 8.57, p = 0.005$], meaning that the pattern of tuning in the AM domain was different for ipsilateral and contralateral masker presentation. No other interactions were significant.

To quantify the sharpness of the masking patterns, the data were fitted with second-order Butterworth bandpass filters (Ewert and Dau, 2000), as was done by Wojtczak and Viemeister (2005) and Moore *et al.* (2009). Such filters are symmetrical on a logarithmic frequency scale, consistent with the shapes of the masking patterns in Fig. 2. The center frequency of each fitted filter was constrained to be equal to the signal frequency. As for the ANOVA described earlier, the data for the two lowest and two highest relative masker frequencies were excluded from the analysis. Table 1 shows the Q values of the fitted filters (center frequency divided by bandwidth at the 3-dB down point) for the individual and mean data. It can be seen that the Q values tend to be smaller, i.e. the filters are less sharp, for contralateral than for ipsilateral presentation. However, an ANOVA with factors signal AM frequency and condition (ipsilateral or contralateral) showed no significant effect of AM

frequency [$F(1, 2) = 12.5, p = 0.071$] or of condition [$F(1, 2) = 2.36, p = 0.265$]. The interaction was also not significant: $F(1, 2) = 1.14, p = 0.40$.

The Q values are similar to but slightly higher than those reported by Wojtczak and Viemeister (2005) for 20, 40, and 80-Hz signal AM and are similar to those reported by Moore *et al.* (2009) for 80-Hz signal AM.

Subject	Signal AM frequency = 40 Hz		Signal AM frequency = 80 Hz	
	Ipsilateral	Contralateral	Ipsilateral	Contralateral
S1	0.87 (1.5)	0.67 (0.7)	1.1 (1.1)	0.96 (1.7)
S2	1.2 (1.4)	1.1 (1.6)	1.4 (1.4)	1.3 (2.0)
S3	2.4 (1.2)	0.83 (1.0)	1.8 (1.8)	1.6 (2.4)
Mean	1.5 (1.3)	0.80 (0.7)	1.4 (1.0)	1.25 (2.0)

Table I. Q values of the second-order Butterworth filters fitted to the individual and mean data presented in Fig. 2 for each condition (ipsi- or contralateral) and signal AM frequency (40 or 80 Hz). Numbers in parentheses show the root-mean-square error (in dB) of the fits.

IV. DISCUSSION

Clear forward masking in the AM domain was found when the signal and masker AM were applied to opposite ears. This finding differs from that of Gutschalk *et al.* (2008), who investigated the effect of adaption to a 60-s long pulse train with an average frequency of 100 Hz on the subsequent detection of AM. They found that thresholds for detecting sinusoidal AM applied to a noise carrier and presented after the adaptor, were elevated for AM frequencies from 100 to 500 Hz when the signal AM was presented to the same ear as the adaptor, but not when the signal AM was presented to the opposite ear. It is not clear why AM forward masking using relatively brief masker AM (about 500 ms in the present study) occurs across ears, but longer-term adaptation to AM does not lead to an effect across ears. It is possible that the lack of contralateral transfer found by Gutschalk *et al.* (2008) reflects the

high AM frequency used by them, but we found contralateral AM forward masking for an 80-Hz AM masker, and this is only a little lower than the 100-Hz frequency used by Gutschalk *et al.* (2008). It is noteworthy that adaptation to a frequency-modulated sinusoidal carrier does affect the threshold for detecting frequency modulation applied to a carrier in the opposite ear (Kay and Mathews, 1972).

The fact that forward masking in the AM domain was found when the signal and masker AM were applied to opposite ears suggests that part of the forward masking effect occurs higher in the auditory pathway than the earliest point of binaural interaction, which is the superior olive (Palmer, 1995). Given that the contralateral masking showed tuning in the AM domain, and hence presumably reflects the operation of the MFB, the results suggest that the MFB resides at least partly after the point in the auditory pathway where binaural interaction occurs. However, the masked thresholds were lower for contralateral than for ipsilateral forward masking. This could mean that there is more than one MFB, with one MFB occurring after the point of binaural interaction and with independent MFBs for the left and right ears, as for the second of the two models described by Thompson and Dau (2008). If so, this would mean that subjects could not attend exclusively to the outputs of the monaural MFBs, even if this would be the best strategy. Alternatively, the MFB might occur entirely at a higher level than the superior olive, but it may receive inputs from both monaural pathways and binaural pathways.

A relatively central site for the MFB is consistent with the results of Malone *et al.* (2015). They measured neural responses to AM tones in the auditory cortex of awake squirrel monkeys. They found that presentation of “masker” AM of a given frequency (4, 10, 32, or 96 Hz) produced suppression of the firing rate to “signal” AM presented subsequently. The effect showed broad tuning in the AM domain. The masker AM did not affect neural synchrony to the signal AM. Malone *et al.* (2015) concluded that “modulation-frequency-specific rate suppression is broadly consistent with the operation of a modulation filterbank” and that “modulation masking may be instantiated in the forebrain” (page 5913).

It should be emphasized that the discussion in terms of one or more MFBs is speculative, since the physiological basis of AM forward masking is not known. It may be the

case that AM forward masking is governed primarily by the perceptual similarity of the masker AM and signal AM, as appears to be the case for modulation detection interference (MDI) (Yost and Sheft, 1989; Yost et al., 1989; Moore and Shailer, 1992). MDI has also been observed when the masker and signal modulation are presented non-simultaneously (Oxenham and Dau, 2001; Gockel et al., 2002). It has been argued that MDI primarily reflects a form of informational masking (Sheft and Yost, 2007). This may also be the case for AM forward masking. It may be that informational masking is stronger when the masker AM and signal AM are presented to the same ear than when they are presented to opposite ears.

The significant interaction of f_s and relative masker frequency and the significant interaction of ear of presentation and relative masker frequency partly reflect the fact that the masking patterns were somewhat more sharply peaked for the 40-Hz than for the 80-Hz signal frequency, especially for the ipsilateral condition. Note that for S1 the ipsilateral threshold for $f_m = f_s = 40$ Hz was probably underestimated because one run was aborted owing to the 0-dB limit imposed on the AM depth. The masking pattern for S1 would have been sharper for $f_s = 40$ Hz if this underestimation had not occurred. The relatively sharp peak for the ipsilateral condition for $f_s = 40$ Hz may partly reflect confusion of the signal and the masker AM when the two had the same frequency and a similar AM depth; the subject may have heard the signal AM but it may have sounded like the masker AM and it may have been difficult for the subject to decide whether the masker AM had ended and the signal AM had started or whether the masker AM had continued. This is analogous to the confusion effects that have been observed for forward masking in the audio-frequency domain (Terry and Moore, 1977; Moore and Glasberg, 1983; Moore and Glasberg, 1985; Neff, 1986).

Wojtczak and Viemeister (2005) assessed the possible existence of confusion in ipsilateral AM forward masking for two subjects who could not perform the task when $f_m = f_s = 40$ Hz and when there was no delay between the end of the masker AM and the start of the signal AM. They used a noise carrier, and investigated the effect of providing a cue to indicate when the masker AM ended. One cue, called the tonal cue, was a 4-kHz sinewave that was presented to the same ear as the noise carrier and was gated synchronously with the

masker AM. The other cue, called the binaural cue, was an independent sample of the noise carrier that was presented to the contralateral ear and which contained masker AM but not signal AM. The tonal cue led to improvements in the signal AM threshold for delays between the signal and masker AM up to 15 ms, consistent with a confusion effect in the absence of a cue. The binaural cue did not lead to improved signal AM thresholds for any delay. The authors suggested that the binaural cue “may have provided distraction, causing a slight increase in forward masking” for short delays. Wojtczak and Viemeister (2005) concluded that confusion effects were probably small, although they also stated that the cues used may not have been effective in reducing confusion. In any case, the magnitude of confusion effects may depend on whether the carrier is a broadband noise, as used by Wojtczak and Viemeister (2005), or a sinusoid, as used in the present study and by Moore *et al.* (2009).

Performance in the AM forward-masking task when the signal and masker AM have the same frequency may depend on the ability to detect the gap in the AM between the masker and the signal. Thresholds for detecting gaps in AM imposed on a high-frequency sinusoidal carrier are roughly proportional to the AM period (Sék and Moore, 2002). The AM gap threshold would have been higher for the 40-Hz signal AM than for the 80-Hz signal AM, and this could account for the finding that the ipsilateral masking patterns were sharply peaked for the 40-Hz but not for the 80-Hz signal AM. Confusion effects in forward masking are unlikely when the signal AM and masker AM are presented to opposite ears, which can account for why the masking patterns showed slightly less sharp peaks for contralateral than for ipsilateral presentation. The tuning in the AM domain for the contralateral condition may therefore give a more accurate estimate of the selectivity of the MFB than the tuning in the ipsilateral condition.

IV. CONCLUSIONS

- (1) AM forward masking occurred in the modulation domain when the signal AM was applied to one ear and the masker AM was applied to the other ear (contralateral condition).
- (2) AM masking in the contralateral condition was smaller than found when the signal AM was applied to the same ear as the masker AM (ipsilateral condition), but in both conditions

the AM forward masking was greatest when the masker AM frequency was similar to the signal AM frequency, reflecting tuning in the AM domain.

(3) The results are consistent with the idea that there is a modulation filter bank that occurs higher in the auditory pathway than the point of binaural interaction.

(4) The masking patterns tended to show sharper peaks in the AM frequency domain for the ipsilateral than for the contralateral condition, perhaps reflecting confusion of the signal and masker AM in the ipsilateral condition when the signal and masker had the same AM frequency. However, the estimated Q values of the masking patterns did not differ significantly for the ipsilateral and contralateral conditions. Testing with a greater number of subjects would be desirable to assess whether selectivity in the AM domain differs for the ipsilateral and contralateral conditions.

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