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Modulation masking produced by a low-frequency pure tone

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ABSTRACT

An intense low-frequency tone can affect the perception of amplitude modulation (AM) applied to a high-frequency carrier. Here, thresholds for detecting AM of a 3000-Hz carrier were measured in the presence of a 50-Hz pure tone at 91 dB SPL. When the carrier was presented at 20 dB sensation level (SL), the thresholds were higher than in the absence of the 50-Hz tone, increased when the AM frequency was increased from 20 to 100 Hz, and did not show a maximum near 50 Hz, as would be expected if the effect of the 50-Hz tone resulted from modulation detection interference. When the AM frequency was fixed at 50 Hz, the AM detection thresholds showed a minimum when the phase of the AM was 90° ahead of the phase of the 50-Hz tone (denoted $\Delta\varphi = 90^\circ$) and a maximum for $\Delta\varphi = 270^\circ$. To assess the role of the outer hair cells (OHCs), AM detection thresholds were measured as a function of $\Delta\varphi$ using SLs of 20 and 50 dB for normal-hearing participants and 20 dB for hearing-impaired participants. It was assumed that the latter would have impaired OHC function. The pattern of the results was similar across SLs and groups: AM detection thresholds were 8–10 dB lower for $\Delta\varphi = 90^\circ$ than for $\Delta\varphi = 270^\circ$ in all cases. This suggests that the OHCs do not play a large role in these effects and supports the idea that the low-frequency tone biases the responses of inner hair cells tuned to high frequencies.

1. Introduction

A low-frequency tone produces a travelling wave in the cochlea that has maximum amplitude near the apex but passes through places that are tuned to higher frequencies (von Békésy, 1947). It is not surprising that this leads to masking effects that can be explained using the concept of excitation patterns (Zwicker, 1956; Glasberg and Moore, 1990). However, sometimes a low-frequency sound can produce effects on the perception of high-frequency sounds that are hard to explain in terms of spread of excitation. In the present work, we study the effect of an intense low-frequency pure tone on the detection of amplitude-modulation (AM) imposed on a high-frequency sinusoidal carrier, with the aim of improving understanding of the underlying mechanisms, especially when it is unlikely that the effects of the low-frequency tone can be explained in terms of spread of excitation.

Deatherage and Henderson (1967) measured the ability to detect a very short 3150-Hz tone as a function of its temporal position within the cycle of a synchronously presented 50-Hz tone, i.e. its position relative to the phase of the 50-Hz tone. Performance was best when the phase was between 200° and 360° and was worst when the phase was between 0° and 180° The effect was greatest when the low-frequency tone was itself inaudible, and hence was unlikely to produce significant spread of excitation to the frequency region of the 3150-Hz tone. When the level of the 50-Hz tone was −5 dB sensation level (SL) and the 3150-Hz tone was fixed at a level that produced 85% correct without the 50-Hz tone, in a two-alternative forced-choice task the two participants scored 91% correct for a phase of 90° and 81% for a phase of 270°. The authors suggested that the phase effects were related to the process underlying the transduction of mechanical to neural energy in the cochlea.

Zwicker conducted similar experiments using low-frequency "maskers" with frequencies of 50, 100 and 200 Hz (Zwicker, 1976c) and using masker frequencies as low as 20 Hz (Zwicker, 1976b). He also found that the threshold for detecting a brief high-frequency tone pip varied according to its position within the cycle of the low-frequency masker. The phase effects were quite complex for very low masker frequencies and high masker levels, but the thresholds for detecting the brief high-frequency tone pip were generally lowest when the tone pip fell close to a maximum in the waveform of the low-frequency tone, as found by Deatherage and

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Henderson (1967). However, Zwicker chose the stimulus parameters such that the masker was likely to produce supra-threshold excitation at the signal frequency. Zwicker's results were based on a single participant, namely himself. Zwicker (1976b) presented a model to explain his results, based upon the idea that the excitation evoked by the low-frequency tone affects the response of the cochlea at the place tuned to the high-frequency tone pip.

McFadden (1975) reported that beats could be heard when a complex tone containing two frequency components separated by Δf (where Δf is less than about 5 Hz) was presented simultaneously with a low-frequency tone with a frequency slightly different from Δf. For the effect to be heard, the low-frequency tone had to be 10–15 dB higher in level than the components of the complex tone. McFadden argued that the beat percept could be explained in terms of interactions on the basilar membrane and that the low-frequency tone needed to produce sufficient vibration at the place on the basilar membrane where the two-tone complex led to maximum displacement. In other words, his explanation involved overlap of the excitation patterns of the low-frequency tone and the two-component complex.

Wakefield and Viemeister (1985) investigated thresholds for detecting AM imposed on a high-frequency bandpass-filtered noise using modulation frequencies (f_m) of 100, 200, 400 Hz in the presence of a pure tone with frequency $= f_m$. They tested five participants. They varied the phase difference between the AM and the low-frequency tone, which is denoted here $\Delta\varphi$. The AM detection threshold was lowest when the phase of the AM was 90° ahead of the phase of the low-frequency tone ($\Delta\varphi = 90°$) and highest when it was about 270°. The results varied somewhat across participants. For a low-frequency tone level of 90 dB SPL, the values of the minimum AM detection thresholds, expressed as $20\log_{10}m$, where m is the modulation index, were below −20 dB for all participants, while some participants were not able to detect 100% AM ($m = 0$ dB) for $\Delta\varphi = 270°$. The effect of $\Delta\varphi$ became less pronounced with increasing carrier level: when the low-frequency tone had a level of 90 dB SPL, for a carrier level of 25 dB sensation level (SL) the difference between maximum and minimum AM detection threshold was 13 dB on average, while the difference was not significant for two participants at 45 dB SL or higher and decreased to 7 dB for the other three participants at 65 dB SL. Wakefield and Viemeister suggested that the phase effects found in their data reflect either an additive process, as proposed by Zwicker (1976b), or a time-varying form of suppression.

Measurements of the displacement of the basilar membrane in animals have shown modulation of the response to a high-frequency tone produced by an intense low-frequency tone (Patuzzi et al., 1984; Temchin et al., 1997). The maximum reduction in the mechanical response was observed when the low-frequency tone produced peak displacement towards scala tympani. Notably, this modulation was not present in dead animals. This strongly suggests that the effect found in living animals depends on the active mechanism of the cochlea, which in turn depends on the operation of the outer hair cells (OHCs) (Robles and Ruggero, 2001). If this modulation of sensitivity is responsible for the psychoacoustical effects found in humans, as reviewed above, the psychoacoustical effects should be reduced or absent for hearing-impaired humans, since hearing loss usually reflects reduced function of the OHCs in the cochlea (Robles and Ruggero, 2001; Moore, 2007). That prediction was tested in this paper.

Nam and Guinan (2018) studied the responses of neurons tuned to high frequencies in cats. They measured responses to tones with frequencies below, above and at the characteristic frequency (CF) in the presence of a 50-Hz "bias tone". They found that the responses to CF, tail-frequency, and "side-lobe" tones were usually suppressed at the same bias-tone phase. They argued that the bias tone alters the mechano-electric-transduction operating point of the stereocilia of the OHCs and that auditory-nerve response enhancements occur due to enhanced motion of the reticular lamina (RL) that drives the deflection of the stereocilia of inner hair cells (IHCs) via RL-tectorial membrane (TM) shear and/or by changing the RL-TM gap.

If the low-frequency pure tone directly biases the IHCs, best detection of a high-frequency tone would be expected when the tone pip is presented at 90° phase of the low-frequency tone and worst detection at a phase 270° as found by Deatherage and Henderson (1967) and by Zwicker (1976a) and Zwicker (1976b). This is because IHCs respond predominantly to the velocity of the basilar membrane (Ruggero et al., 1996; Cheatham and Dallos, 1999), i.e. the derivative of the basilar membrane displacement, although there are probably multiple drive mechanisms, depending on sound level and on the frequency of the stimulating tone relative to the CF (Guinan, 2012). In the case of an AM carrier, as used by Wakefield and Viemeister (1985), the low-frequency tone might increase the effective AM depth when $\Delta\varphi = 90°$ and decrease the effective AM depth when $\Delta\varphi = 270°$, which would account for the observed pattern of results.

So far, we have considered explanations for the effects of low-frequency tones on the perception of high-frequency sounds in terms of cochlear mechanisms. However, it is possible that a more central mechanism is involved. While sinusoids with very low frequencies are perceived as steady, they also sound somewhat rough, like a sound with AM (Terhardt, 1974). For example, an intense 50-Hz tone will give rise to bursts of nerve spikes separated by 20 ms and this may lead to the sensation of roughness. Since an intense low-frequency tone leads to a temporal pattern of neural responses similar to that produced by an AM tone, it is possible that the effect of a low-frequency sinusoid on the detection of AM of a high-frequency carrier is caused by a form of across-frequency modulation masking, similar to the masking of AM on one carrier produced by AM on a different carrier, which is often called modulation detection interference (MDI, Yost et al., 1989; Yost and Sheft, 1989; Bacon and Moore, 1993). MDI shows some degree of tuning in the AM domain (Yost and Sheft, 1989; Bacon and Moore, 1993; Moore et al., 1991). For example, for a masker with $f_m = 50$ Hz, MDI decreases from about 8 dB for a target with $f_m = 50$ Hz to about 5 dB for a target with $f_m = 20$ or 100 Hz (Yost et al., 1989). Hence, if the effect of a low-frequency tone on the perception of AM of high-frequency signals reflects a form of MDI, one would expect the effect of the low-frequency tone to be greatest when its frequency is close to f_m and to decrease gradually for lower and higher frequencies. That prediction was tested in this paper.

In the present work we modified and extended the experiments of Wakefield and Viemeister (1985). We wanted to focus on effects that are unlikely to be caused by spread of excitation in the cochlea. To decrease the likelihood of the low-frequency tone producing significant excitation at the signal frequency, we used a 50-Hz low-frequency tone rather than the frequencies of 100 to 400 Hz used by Wakefield and Viemeister (1985). To avoid the effect of intrinsic amplitude fluctuations in the signal carrier (Dau et al., 1997), we used a 3000-Hz sinusoidal carrier rather than a bandpass filtered noise carrier. Some recent research using cats (Nam and Guinan, 2018) suggests that a 90-dB 50-Hz tone can modulate the operating point of the OHCs at 2500 Hz, hence affecting the response of the basilar membrane. To assess whether there was any significant suppression or excitation produced by the 50-Hz tone at the place tuned to 3000 Hz, we measured the threshold for detecting a 3000-Hz tone both in quiet and in the presence of a 50-Hz tone.

In summary, the main goals of the experiments were as follow. Experiment 1 measured the tuning of the effect of the low-frequency tone in the AM domain using signal AM frequencies between 20 and 100 Hz to assess the possible role of MDI. Experiment 2 assessed the effect of the phase difference between the 50-Hz tone and the 50-Hz AM applied to the 3000-Hz carrier to assess whether the phase effect was the same as observed by Wakefield and Viemeister (1985) for higher frequencies of the low-frequency tone. Experiment 3 assessed the effect of phase difference, level of the 3000-Hz carrier, and hearing status (normal or impaired). We expected that if the phase effect depended on the integrity of the OHCs, then the effect would be reduced or absent for the hearing-impaired participants. Since previous studies in this area have revealed marked individual differences, at least 18 participants were used in each experiment.

2. Method

All three experiments measured the effect of a 50-Hz sinusoid on the ability to detect AM of a 3000-Hz sinusoidal carrier.

2.1. Participants

The same 20 normal-hearing (NH) participants took part in Experiments 1 and 2. They were aged 20 to 31 years and had audiometric thresholds not higher than 20 dB HL for both ears and for all audiometric frequencies between 125 and 8000 Hz. The audiometric threshold at 3000 Hz for the single ear that was tested in the experiments was better than or equal to 15 dB HL.

Nine NH participants, who did not take part in Experiments 1 and 2 and were aged 20 to 22 years, and nine hearing-impaired (HI) participants, who were aged 70 to 80 years, took part in Experiment 3. The HI participants had audiometric thresholds between 35 and 55 dB HL at 3000 Hz for their better-hearing ear, which was the one tested.

2.2. Apparatus

The experiments took place in a sound-attenuating booth. Stimuli were generated digitally at a sampling rate of 48 kHz, digital-to-analog converted by an M-Audio Delta 44 audio interface (Cumberland, UK) with 24-bit resolution, passed through a Hatfield 2125 manual attenuator (Hatfield, UK), and presented via one earpiece of Sennheiser HD 580 headphones (Wedemark, Germany). An important characteristic of the headphones is the phase response. For the Sennheiser HD 580, the difference in group delay between 50 Hz and 3000 Hz is smaller than 10° of a 50-Hz cycle (Phillips, 2006), which is rather small and so was not considered in our analyses.

2.3. Stimuli and design

All stimuli for the main experiments consisted of a 50-Hz sinusoid and a 3000-Hz amplitude-modulated sinusoidal carrier. Allowing for the frequency response of the Sennheiser HD 580 headphones, the effective level at the eardrum, as assessed using a dummy head (Burkhard and Sachs, 1975) was 91 dB SPL. Note that while the SPL of the 50-Hz tone was high, it was not uncomfortably loud, because transmission through the middle ear becomes progressively less effective when the frequency is reduced below 500 Hz and because the gain provided by the active mechanism in the cochlea is probably reduced at very low frequencies (Moore et al., 1997; Cooper and Rhode, 1995; Robles and Ruggero, 2001).

According to the excitation-pattern model for normal hearing of Glasberg and Moore (1990), the 50-Hz tone produced an excitation level of -13.3 dB at 3000 Hz. Thus, the 50-Hz tone was not expected to have an effect on the perception of the 3000-Hz tone via spread of excitation. Note that the model of Glasberg and Moore is based on data from simultaneous masking experiments and therefore includes any effects of suppression on masking (Moore and Vickers, 1997; Delgutte, 1990). Hence, suppression effects produced by the 50-Hz tone were also expected to be negligible at 3000 Hz. The same holds for hearing-impaired listening: for example, for a typical moderately sloping moderate hearing loss (N3, Bisgaard et al., 2010) with 90% of the hearing loss attributed to reduced OHC function, the excitation level at 3000 Hz would be 35.2 dB according to the excitation-pattern model of Moore and Glasberg (2004). This excitation level is higher than for normal hearing due to the broader auditory filters in the impaired ear but is still considerably less than the threshold of 55 dB HL at 3000 Hz (corresponding to about 65 dB SPL) for this hearing loss. Likewise, the excitation level is 26.3 dB at 3000 Hz for a mild hearing loss (N2) with a threshold of 40 dB HL at 3000 Hz, and 7.4 dB for a very mild hearing loss with a threshold of 20 dB HL at 3000 Hz. In order not to rely on a model alone, detection thresholds for a 3000-Hz pure tone were measured both in quiet and in the presence of the 50-Hz tone. Those thresholds were not significantly different (see Section 2.4).

In Experiment 1, that assessed the possible role of MDI, the 3000-Hz carrier was presented at 20 dB SL and was amplitude modulated with f_m of 20, 30, 40, 50, 60, 80 and 100 Hz. At the start of the stimuli, a peak in the waveform of the 50-Hz tone coincided with a peak in the envelope of the 3000-Hz carrier. When $f_m = 50$ Hz, the peaks of the waveform of the 50-Hz tone and of the envelope of the 3000-Hz carrier coincided throughout the stimuli, as illustrated in the left panel of Fig. 1 (under the assumption that the headphones had only a small difference in group delay between 50 and 3000 Hz). Since all other values of f_m were integer multiples of 10 Hz, the phase of the 50-Hz tone relative to that of the AM shifted across cycles, but the pattern repeated every 100 ms.

In Experiment 2, which assessed the effect of phase difference, the 3000-Hz carrier had a level of 20 dB SL and f_m was set to 50 Hz. The phase difference between the AM tone and the 50-Hz pure tone ($\Delta\varphi$) was 0, 90, 180, 270, 300 or 330°. The finer steps between 270 and 0° were added because this range led to the highest AM detection thresholds in pilot tests.

A value of $\Delta\varphi$ between 0 and 180° meant that the phase of the AM was equal to or ahead of the phase of the 50-Hz pure tone. This is illustrated in Fig. 1. The left panel shows a stimulus with no phase difference ($\Delta\varphi = 0$). The peaks of the waveform of the 50-Hz tone and of the envelope of the 3000-Hz carrier coincide. The right panel shows a 90° phase difference, the phase of the AM being ahead by 90°.

Experiment 3 was similar to Experiment 2 but the effects of the level of the 3000-Hz carrier and hearing status were assessed to investigate a possible role of OHCs. The 3000-Hz carrier had levels of 20 and 50 dB SL for the NH participants, and 20 dB SL for the HI participants. The average detection threshold in quiet at 3000 Hz was -2.8 dB SPL for the NH participants and 44 dB SPL for the HI participants (standard deviation = 10 dB for both groups). Thus, the 50-dB SL stimuli used with the NH group had a somewhat higher average level than the 20-dB SL stimuli used with the HI group, on average by 17 dB. The value of $\Delta\varphi$ ranged from 0 to 315° in steps of 45°.

The duration of the stimuli was 1 s in all experiments and tests, except for the audiogram.

2.4. Procedure

Firstly, an audiogram was obtained for each participant for both ears, for all audiometric frequencies between 125 and 8000 Hz, using a Grason-Stadler GSI61 audiometer (Eden Prairie, MN) and the method recommended by the British Society of Audiology (2018).

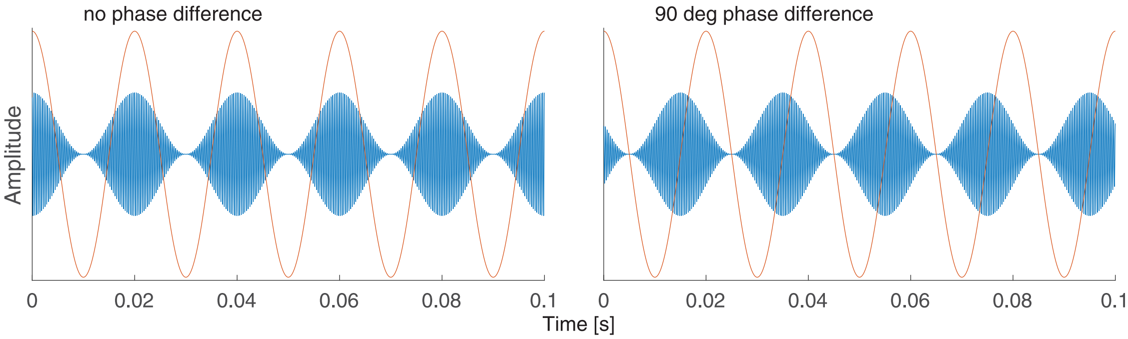

Fig. 1. Depiction of the first 100 ms of stimuli with no phase difference ($\Delta\varphi = 0$, left panel) and 90° phase difference ($\Delta\varphi = 90°$, right panel) between the 50-Hz sinusoid (red curve with larger amplitude) and the AM of the 3000-Hz carrier (blue curve). For ease of visualization, the level of the 50-Hz tone relative to the 3000-Hz carrier was set much lower than the value used in the experiments. Also, for simplicity, the rise and fall ramps used in the experiments are not shown in the figure.

Secondly, the absolute threshold for detecting a 3000-Hz pure tone was determined with the Sennheiser HD 580 headphones, in order to set the SL. Then, the threshold for detecting a 3000-Hz pure tone in the presence of a 50-Hz 91-dB SPL masker was determined. Then, the AM detection threshold was determined for a 3000-Hz 20-dB SL pure tone that was modulated at a rate of 50 Hz. For the NH participants tested in Experiment 3, the AM detection threshold was also measured using a level of 50 dB SL. Finally, the main experiments were conducted.

2.4.1. Determination of the threshold in quiet at 3000 Hz

The absolute threshold at 3000 Hz was determined for the better ear using a two-interval two-alternative forced-choice (2I2AFC) 1-up/2-down procedure (Levitt, 1971). One interval contained the pure tone with a duration of 1 s and 3.3-ms raised-cosine rise and fall ramps, and the other interval contained 1 s of silence. The intervals were marked by the responses buttons on the screen being highlighted in color during the interval. The task was to indicate the interval in which a tone occurred. The level started at 40 dB SPL for the NH participants and 60 dB SPL for the HI participants. It was decreased or increased by 5 dB until two reversals occurred, then by 3 dB until two more reversals occurred, and then by 1 dB until six more reversals occurred. The mean level at the last four reversals was taken as the threshold for that run. Two runs were obtained for each participant and the mean for the two runs was taken as the absolute threshold.

2.4.2. Determination of the threshold at 3000 Hz in the presence of a 50-Hz masker

The procedure was identical to that for determining the threshold in quiet, except that both intervals contained a 50-Hz 91-dB SPL sinusoid, the fall and rise times were 100 ms for both tones, and only one run was conducted. This was done to check that the 50-Hz sinusoid did not have a direct masking effect on the 3000-Hz sinusoid. The mean difference across all 38 participants between the threshold with the 50-Hz sinusoid and without it was 1.7 dB (standard deviation = 7.2 dB), which was not statistically significant, $t(37) = 1.47$, $p = 0.149$. Thus, as expected from the excitation-pattern model of Glasberg and Moore (1990), the 50-Hz sinusoid did not have a significant direct masking effect on the 3000-Hz sinusoid.

2.4.3. Amplitude-modulation detection threshold in quiet

The AM detection threshold for a carrier frequency of 3000 Hz and $f_m = 50$ Hz was determined using a 2I2AFC 1-up/2-down procedure. One interval contained an AM sinusoid and the other interval contained an unmodulated sinusoid with the same root-mean-square level. The task was to determine the interval that contained the modulated sound ("Which of the two sounds wobbled?"). Rise and fall times were 150 ms. The starting m was 0.4. The value of m was changed by a factor of 2 until two reversals occurred, then by a factor of 1.4 until two more reversals occurred and by a factor of 1.2 for four more reversals. If the adaptive procedure called for a value of m greater than 1, it was set to 1. The mean value $20\log_{10}m$ at the last four reversals was taken as the AM detection threshold for that run.

For Experiments 1 and 2, the final AM detection threshold was taken as the mean of two runs, one obtained before the main experiment and one after. The mean of the absolute value of the difference between the two runs was 3.1 dB (standard deviation = 2.4 dB). For Experiment 3, the AM detection threshold was determined once with the carrier at 20 dB SL and 50 dB SL for the NH participants and at 20 dB SL for the HI participants. It was measured only once for each level in Experiment 3 because the participants were available only for a limited time and the focus was on the main experiment. It was measured twice for one HI participant because the threshold determined in the first run was much higher than expected from the audiogram.

2.4.4. Amplitude-modulation detection threshold in the presence of a 50-Hz tone

A single run of the main experiments followed the same procedure as described for AM detection, except that a 50-Hz 91-dB-SPL pure tone was present in both intervals. All other parameters were the same, as was the task of selecting in which of the two intervals the sound "wobbled".

Experiments 1 and 2 were conducted in one session, and their conditions were interleaved. The run with $f_m = 50$ Hz and $\Delta\varphi = 0$ was used in the analysis of both experiments. Experiment 1 had six further runs with $f_m = 20$, 30, 40, 60, 80 and 100 Hz. Experiment 2 had five further runs with $\Delta\varphi = 90$, 180, 270, 300 and 330°. The twelve conditions were presented in a random order, which was the same for the first ten participants and reversed for the other ten participants.

In Experiment 3, eight runs with $\Delta\varphi$ varied from 0 to 315° in steps of 45° were presented in random order. Half of the NH participants were tested first at 20 dB SL and then at 50 dB SL, and the other half were tested in the reverse order.

3. Results

The mean results of Experiment 1 are shown in Fig. 2. The AM detection threshold in quiet (without the 50-Hz sinusoid) for a 3000-Hz carrier modulated at $f_m = 50$ Hz is shown on the left. The AM detection thresholds in the presence of the 50-Hz sinusoid were higher than the threshold in quiet and tended to increase with increasing f_m, ranging from -16 dB for $f_m = 20$ Hz to -9 dB for $f_m = 100$ Hz, but with a slight dip for $f_m = 50$ Hz, for which

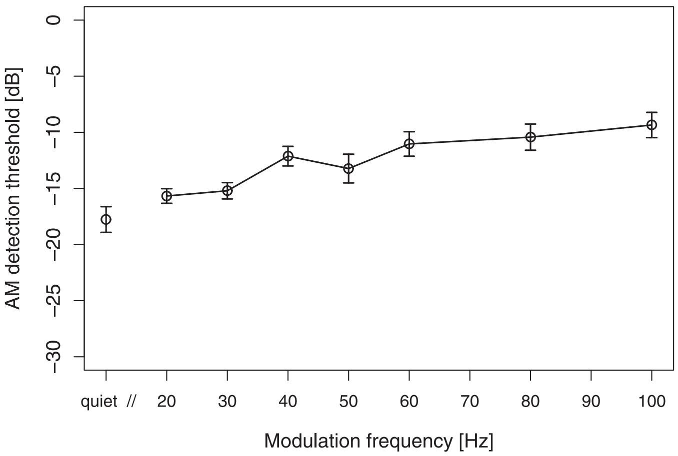

Fig. 2. Thresholds for detecting AM of a 3000-Hz carrier in quiet (far left, $f_m = 50$ Hz only) and in the presence of a 50-Hz 91-dB SPL sinusoid as a function of modulation frequency. Circles show means across participants and error bars show ± 1 standard error. The 50-Hz sinusoid and the AM started in phase for all conditions.

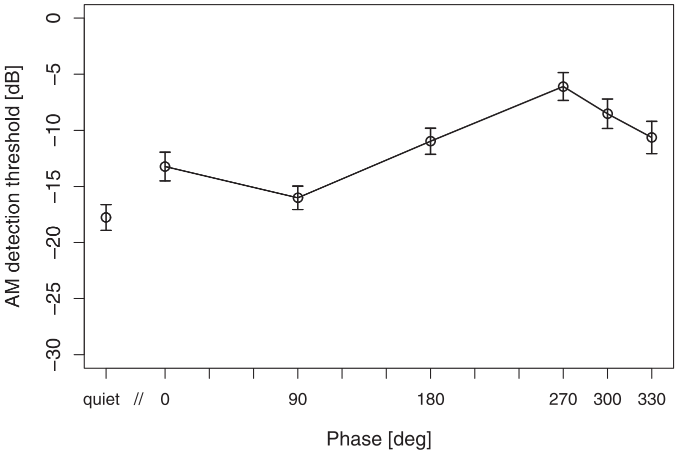

Fig. 3. Thresholds for detecting 50-Hz AM of a 3000-Hz carrier in quiet (far left) and in the presence of a 50-Hz 91-dB SPL sinusoid as a function of the phase difference between the 50-Hz sinusoid and the AM. Circles show means across participants and error bars show ± 1 standard error.

the threshold was −13 dB. However, Fig. 2 shows the threshold for detecting 50-Hz AM only for $\Delta\varphi = 0$. The AM detection threshold for $f_m = 50$ Hz varied from −16 dB to −6 dB, depending on $\Delta\varphi$.

A one-way within-subjects analysis of variance (ANOVA) on the AM thresholds obtained in the presence of the 50-Hz sinusoid showed a significant main effect of f_m, $F(6,114) = 12.1$, $p < 0.001$, $\eta_p = 0.39$. Also, note that none of the error bars for the AM thresholds obtained in the presence of the 50-Hz sinusoid overlap with that for the AM detection threshold in quiet. In summary, the 50-Hz sinusoid produced AM masking, but the masking was not maximal when $f_m = 50$ Hz. AM masking increased with increasing f_m and thus was maximal at the highest f_m that was tested, 100 Hz.

Fig. 3 shows the results of Experiment 2. The AM detection threshold of a 3000-Hz sinusoid modulated at a rate of 50 Hz in the presence of a 50-Hz sinusoid was measured as a function of $\Delta\varphi$. All thresholds measured in the presence of the 50-Hz sinusoid were higher than the threshold measured in quiet (far left). The AM detection threshold was lowest (−16 dB) for $\Delta\varphi = 90°$, which is close to the threshold in quiet of −18 dB. The highest threshold of −6 dB occurred for $\Delta\varphi = 270°$. At this value of $\Delta\varphi$, the peaks in the waveform of the 50-Hz sinusoid preceded the peaks in the modulator by 5 ms.

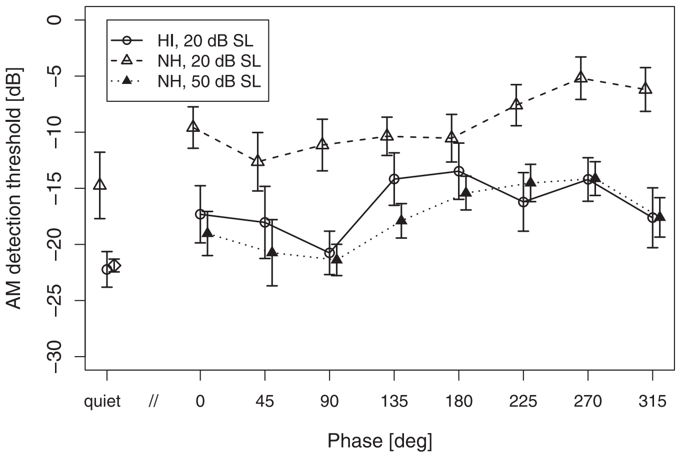

Fig. 4. As Fig. 3 but for NH participants tested at 20 dB SL (dashed line with open triangles) and 50 dB SL (dotted line with filled triangles), and HI participants tested at 20 dB SL (solid line with open circles).

For $\Delta\varphi = 270°$, some participants had difficulty detecting the AM for the maximum possible modulation depth of $m = 1$. In such cases, the adaptive procedure only terminated when enough pairs of correct guesses were made to achieve the required number of reversals. Hence, the “true” mean threshold for $\Delta\varphi = 270°$ is higher than shown in Fig. 3.

A one-way within-subjects ANOVA showed a significant main effect of $\Delta\varphi$, $F(5,95) = 19.2$, $p < 0.001$, $\eta_p = 0.50$. In summary, there was a clear effect of $\Delta\varphi$, AM detection thresholds being lowest for $\Delta\varphi = 90°$ and highest for $\Delta\varphi = 270°$.

Experiment 3 was similar to Experiment 2. However, the focus was on comparing NH and HI participants, and investigating the effect of level of the 3000-Hz carrier within the NH participants. Fig. 4 shows the results. For AM detection in quiet (far left), the HI participants had better (lower) thresholds than the NH participants when tested at the same SL of 20 dB, consistent with previous research (Lüscher and Zwislocki, 1949; Buus et al., 1982b, 1982a; Moore et al., 1992; Füllgrabe et al., 2003; Ernst and Moore, 2012; Sęk et al., 2015; Schlittenlacher and Moore, 2016). However, when tested at similar SPLs (20 dB SL for the HI participants and 50 dB SL for the NH participants), AM detection thresholds in quiet were similar for the HI and NH participants.

The dashed line with triangles shows the results for the NH participants tested at the same SL as used in Experiment 2. The pattern and range of the AM detection thresholds are similar to those for Experiment 2, with a minimum of −13 dB for $\Delta\varphi = 45°$ and a maximum of −5 dB for $\Delta\varphi = 270°$. The thresholds for the HI participants (solid line with circles) at the same SL are markedly lower, with a minimum of −21 dB for $\Delta\varphi = 90°$ and about −13 to −14 dB at 135, 180 and 270°. The AM detection thresholds for the NH participants at 50 dB SL (dotted line with diamonds) were similar to those for the HI participants at 20 dB SL, although the AM thresholds for the HI participants showed a broader maximum over the range 135 - 270°.

Two ANOVAs were calculated to explore the effect of level within the NH participants and the difference between NH and HI participants at the same SL. The two-way (phase × level) within-subjects ANOVA for the NH participants showed significant main effects of phase, $F(7,56) = 5.47$, $p < 0.001$, ${\eta_p}^2 = 0.41$ and of level, $F(1,8) = 41.5$, $p < 0.001$, ${\eta_p}^2 = 0.84$, but no significant interaction, $F(7,56) = 1.07$, $p = 0.39$, ${\eta_p}^2 = 0.12$. The two-way ANOVA with between-subjects factor hearing status and within-subjects factor phase for the results obtained at 20 dB SL showed significant main effects of hearing status, $F(1,16) = 8.35$, $p = 0.01$, ${\eta_p}^2 = 0.34$ and of phase, $F(7{,}112) = 3.59$, $p = 0.002$, $\eta_p{}^2 = 0.18$. The interaction between hearing status and phase was not significant, $F(7{,}112) = 1.93$, $p = 0.07$, $\eta_p{}^2 = 0.11$.

4. Discussion

As described in the introduction, one possible explanation for the effects of a low-frequency tone on the perception of AM of a high-frequency AM tone is in terms of MDI. If the effect of the 50-Hz sinusoid reflected a form of MDI, one would expect the effect to be greatest when $f_m = 50$ Hz and to decrease gradually for lower and higher values of f_m. In fact, the AM detection thresholds tended to increase with increasing f_m, being highest for $f_m = 100$ Hz. This effect may have been caused by variation in sensitivity to AM with changing f_m, since at low SLs thresholds for detecting AM of a high-frequency sinusoidal carrier increase slightly with increasing f_m over the range 20–100 Hz (Kohlrausch et al., 2000; Moore and Glasberg, 2001). Overall, the lack of tuning in the AM domain shown in Fig. 2 does not support an interpretation in terms of MDI.

The pattern of phase effects found in Experiments 2 and 3 is similar to that found by Wakefield and Viemeister (1985). Their experiment was similar to ours, but they used frequencies of 100, 200, and 400 Hz for the low-frequency sinusoid, and the signal AM was applied to a 3-kHz-wide band of noise centered at 10 kHz, rather than to a sinusoidal carrier. For a 400-Hz sinusoid presented at 90 dB SPL, the threshold for detecting AM applied to a noise carrier at 45 dB SL was lowest for $\Delta\varphi \approx 90°$ and highest for $\Delta\varphi \approx 270°$, although the exact pattern varied somewhat across the three participants tested. Also like our findings, the low-frequency sinusoid had little or no masking effect on the high-frequency carrier. Unlike our findings, Wakefield and Viemeister found that a 90-dB SPL low-frequency sinusoid actually improved AM detection relative to that measured in quiet for $\Delta\varphi$ close to 90°. The difference from our results may reflect their use of higher frequencies for the low-frequency tone, which resulted in a higher sensation level than for the low-frequency tone used here. This finding of improved AM detection produced by a low-frequency tone also appears inconsistent with an explanation in terms of MDI. Finally MDI appears to be largely unaffected by the relative phase of the AM applied to the masker and signal carriers (Yost and Sheft, 1989; Moore et al., 1991), whereas we found a significant effect of $\Delta\varphi$, providing more evidence that the effect found here is not related to MDI.

The results for both the NH and HI participants in Experiments 2 and 3 showed a minimum in the AM detection threshold when the phase of the low-frequency sinusoid lagged behind that of the AM of the high-frequency carrier by about 90° For $\Delta\varphi = 90°$, the maximum of the AM coincided with the steepest positive gradient in the waveform of the low-frequency sinusoid (see for example $t = 0.15$ s in Fig. 1). AM detection was most difficult for $\Delta\varphi = 270°$, i.e. when the maximum of the AM coincided with the maximum negative gradient of the pure tone. This pattern of results is consistent with the idea that the low-frequency sinusoid effectively induces AM of the high-frequency carrier; the low-frequency sinusoid increases the effective short-term magnitude of the carrier when the low-frequency sinusoid has its maximum positive gradient and decreases the effective magnitude of the carrier when the low-frequency sinusoid has its maximum negative gradient. For $\Delta\varphi = 270°$, the induced AM may partially cancel the AM in the signal interval, while inducing a small amount of AM in the non-signal interval, making the task difficult or impossible for some participants. For $\Delta\varphi = 90°$, the induced AM may increase the effective AM depth in the signal interval, while again inducing a small amount of AM in the non-signal interval, making the task overall easier and leading to lower AM detection thresholds.

As noted in the introduction, one possible explanation for the results presented here is that the low-frequency sinusoid modulates the basilar-membrane response to the high-frequency carrier. Patuzzi et al. (1984) showed that the simultaneous presentation of an intense low-frequency tone and a lower-intensity high-frequency tone produced modulation of the high-frequency motion of the basilar membrane in the first turn of the guinea pig cochlea. This modulation was synchronized with the displacement caused by the low-frequency tone. Maximum reduction in the response to the high-frequency tone was found when the low-frequency tone produced peak displacement towards scala tympani, whereas a less pronounced reduction was observed for peak displacement towards scala vestibuli. This pattern of results is not consistent with the interpretation given above, namely that the response to a high-frequency sinusoid is increased when the low-frequency sinusoid has a positive gradient and is decreased when the low-frequency sinusoid has a negative gradient. Hence it appears that the phase effect found in our experiments, and those of Wakefield and Viemeister (1985), cannot directly be explained in terms of basilar-membrane responses. However, the present results do not rule out an interaction on the basilar membrane or reticular lamina (Nam and Guinan, 2018) based on a mechanism that is driven by the gradient of the response to the low-frequency tone.

The modulation of the basilar-membrane response to a high-frequency tone produced by a low-frequency tone found by Patuzzi et al. (1984) disappeared post mortem. This suggests that the effect that they found was mediated by the active operation of the OHCs, consistent with the findings of Nam and Guinan (2018). If the OHCs played a role in the effects reported here, then we would expect smaller phase effects for the HI than for the NH participants tested in experiment 3, since sensorineural hearing loss is thought to be partly caused by loss of function of the OHCs (Moore et al., 1999; Robles and Ruggero, 2001; Moore, 2007). In fact, the effect of varying $\Delta\varphi$ was similar for the NH and HI participants. The difference between the maximum and minimum AM thresholds, shown in Fig. 4, was about 8 dB for both HI and NH participants and there was no significant interaction between hearing status and phase. These findings suggest that the OHCs do not play a strong role in producing the phase effects reported here and that the effect has a different origin from those reported by Patuzzi et al. (1984) and Nam and Guinan (2018). A major difference between the present study and these two physiological studies is that the high-frequency tone was not modulated in the physiological studies but was amplitude modulated in our study, and we measured AM detection thresholds, not thresholds for detection of the high-frequency tone.

Our results are consistent with the idea that the IHCs in the cochlea are driven by the velocity of the basilar membrane (Cheatham and Dallos, 1999; Ruggero et al., 1996), i.e. the first derivative of its displacement. The intense low-frequency tone may increase the excitation of the IHCs when the gradient of the waveform of the low-frequency tone is positive, and may reduce the excitation of the IHCs when the gradient is negative. However, it is difficult to predict the effects of varying $\Delta\varphi$ because of effects of the transmission time along the basilar membrane (von Békésy, 1947; Ruggero and Rich, 1987) and the possible influence of micro-mechanical events involving the TM and RL (Ruggero and Rich, 1987; Nam and Guinan, 2018). Also, the phase of the basilar-membrane response that leads to maximum IHC excitation appears to be affected by multiple mechanisms for intense sounds (Kiang et al., 1965; Kiang, 1990; Ruggero et al., 2000; Guinan, 2012).

The effects studied in the present work have practical implications for acoustic scenes with intense low-frequency background noise, for example in the vicinity of wind turbines or in vehicles on rough roads. The low-frequency sounds may effectively induce spurious AM on higher-frequency sounds, including speech, making it harder to extract the intrinsic modulations in the higher-frequency sounds that are important for speech intelligibility (Stone et al., 2011, 2012; Relano-Iborra et al., 2016).

5. Conclusions

(1) Thresholds for detecting AM of a 3000-Hz sinusoidal carrier were higher in the presence than in the absence of a 91-dB-SPL 50-Hz tone, even though it is likely that the 50-Hz tone produced negligible excitation at the place in the cochlea tuned to 3000 Hz.
(2) Thresholds for detecting AM of a 3000-Hz sinusoidal carrier in the presence of the 50-Hz tone did not show a maximum for f_m close to 50 Hz. Rather, AM detection thresholds increased with f_m in a similar way as when measured without the 50-Hz pure tone, although the AM detection thresholds were systematically higher than when the 50-Hz tone was absent. These results are not consistent with the idea that the effect of the low-frequency tone reflects a form of MDI.
(3) The intense 50-Hz pure tone decreased the ability to detect 50-Hz AM of the 3000-Hz carrier by an amount that depended on the phase difference between the AM and the 50-Hz tone; the AM detection threshold was 8 dB higher for $\Delta\varphi = 270°$ than for $\Delta\varphi = 90°$.
(4) The effect of $\Delta\varphi$ was similar for normal-hearing and hearing-impaired participants, and for the former the effect was similar for sensation levels of 20 and 50 dB. This suggests that the OHCs do not play a large role in producing the observed phase effects.
(5) The pattern of the results is consistent with the idea that IHCs are driven by the velocity of the basilar membrane and that the low-frequency tone modulates the responses of the IHCs.

Declarations of Competing Interest

None.

CRediT authorship contribution statement

Josef Schlittenlacher: Methodology, Software, Formal analysis, Data curation, Writing – original draft, Visualization, Supervision. **Ji Xia Lim:** Methodology, Investigation, Formal analysis. **Jemima Lawson:** Methodology, Investigation, Formal analysis. **Brian C.J. Moore:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Supervision, Funding acquisition.

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