Forward masking of frequency modulation^{a)}

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(Received 13 January 2012; revised 20 August 2012; accepted 29 August 2012)

Forward masking of sinusoidal frequency modulation (FM) was measured with three types of maskers: FM, amplitude modulation (AM), and a masker created by combining the magnitude spectrum of an FM tone with random component phases. For the signal FM rates used (5, 20, and 40 Hz), an FM masker raised detection thresholds in terms of frequency deviation by a factor of about 5 relative to without a masker. The AM masker produced a much smaller effect, suggesting that FM-to-AM conversion did not contribute substantially to the FM forward masking. The modulation depth of an FM masker had a nonmonotonic effect, with maximal masking observed at an intermediate value within the range of possible depths, while the random-phase FM masker produced less masking, arguing against a spectrally-based explanation for FM forward masking. Broad FM-rate selectivity for forward masking was observed for both 4-kHz and 500-Hz carriers. Thresholds measured as a function of the masker-signal delay showed slow recovery from FM forward masking, with residual masking for delays up to 500 ms. The FM forward-masking effect resembles that observed for AM [Wojtczak and Viemeister (2005). *J. Acoust. Soc. Am.* **118**, 3198–3210] and may reflect modulation-rate selective neural adaptation to FM.

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PACS number(s): 43.66.Mk, 43.66.Dc [LD]

Pages: 3375–3386

I. INTRODUCTION

Dynamic changes in amplitude and frequency are a common occurrence in natural sounds, including speech and animal vocalizations. Although patterns of the dynamic changes in amplitude and frequency are typically complex, studies of auditory perception often use sinusoidal amplitude modulation (AM) and sinusoidal frequency modulation (FM) to gain an understanding of how these changes are coded in the auditory system and to what extent they contribute to the proper interpretation of a sound by the brain. Several mechanisms have been suggested for representing FM in the auditory system; some are associated with changes in peripheral excitation patterns (e.g., Zwicker, 1962; Hartmann and Hnath, 1982; Moore and Sek, 1994), while others involve so-called “feature coding,” whereby FM is processed by centrally-located neurons that are specialized in responding to changes in frequency (e.g., Kay and Matthews, 1972; Regan and Tansley, 1979; Tansley and Suffield, 1983).

Related to a specific coding mechanism is the question of whether or not AM and FM are detected through a common mechanism (e.g., Zwicker, 1962; Moore and Sek, 1994; Saberi and Hafer, 1995) or via two (or more) independent mechanisms (e.g., Feth, 1972; Kay and Matthews, 1972; Coninx, 1978). Physiological measurements from single units of the primary auditory cortex of different experimental animals show highly correlated best rates and similar patterns of discharge rates for AM and FM, supporting the

common-mechanism hypothesis (e.g., Eggermont, 1994; Liang *et al.*, 2002). Responses to AM and FM obtained using functional magnetic resonance imaging also suggest that common areas of the non-primary auditory cortex in humans are responding to both types of modulation (Hart *et al.*, 2003). Hart *et al.* found no regions that would respond to FM but not to AM, although they identified small areas responding only to AM.

However, a few physiological and psychophysical studies have shown evidence for at least partially independent FM coding. Qin *et al.* (2008) performed a detailed analysis of cortical responses to linear FM in awake cats and identified four different response patterns. They suggested that diverse patterns are needed to represent different FM parameters, such as the frequency deviation, speed, and direction of the frequency sweep. The study by Qin *et al.* corroborated earlier findings by Whitfield and Evans (1965) who found cells that did not respond to pure tones but were easily activated by FM, giving rise to the concept of “feature coding.” According to the feature-coding hypothesis, different dynamic characteristics of sounds, such as AM and FM, would evoke responses in neurons selectively sensitive to these particular characteristics.

In humans, evidence for partial independence of FM and AM coding has been shown using psychophysical methods. Zwicker (1962, 1970) showed that the detection of AM is affected by FM and suggested that both are detected by monitoring a single place in the peripheral excitation pattern, where changes in the excitation level produced by the modulation are the greatest. Moore and Sek (1992, 1996) replicated Zwicker’s results but were unable to account for the effects of relative phases on the detectability of mixed modulation (consisting of both AM and FM simultaneously) using either Zwicker’s single-channel excitation-pattern model, or

^{a)}A portion of this data was presented at the 15th International Symposium on Hearing and published in its proceedings (Viemeister *et al.*, 2010a, *The Neurophysiological Bases of Auditory Perception*).

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its multiband version in which changes in excitation level were integrated across the entire excitation pattern (e.g., Florentine and Buus, 1981). Similarly, the data of Edwards and Viemeister (1994a,b) implied at least partial independence of the mechanisms involved in AM and FM coding. Moore and Sek (1995, 1996) suggested that at low carrier and modulation frequencies, AM and FM are partially coded by the same excitation-pattern mechanism but FM is additionally represented in the auditory nerve by the phase-locked responses to the temporal fine structure in the frequency sweeps. A similar conclusion was drawn by Lacher-Fougère and Demany (1998) based on the observation that thresholds for AM and FM showed different patterns of dependence on modulation rates between 2 and 10 Hz, when a low carrier frequency was used (Demany and Semal, 1986; Moore and Sek, 1995; Lacher-Fougère and Demany, 1998).

Early psychophysical support for the feature-coding mechanism was obtained from studies using adaptation paradigms (Kay and Matthews, 1972; Regan and Tansley, 1979; Tansley and Suffield, 1983). It was hypothesized that a long exposure to AM would affect sensitivity to AM but not FM and vice versa. The results were generally consistent with this hypothesis, although small amounts of threshold elevation were observed for detecting AM after long exposures to an FM adaptor. However, the validity of these results was later questioned by studies which showed that the change in detection threshold believed to reflect adaptation disappeared with training (Moody *et al.*, 1984; Bruckert *et al.*, 2006). The shift in thresholds for detecting linear frequency sweeps observed by Gardner and Wilson (1979), after exposure to the same-direction sweeps, was initially interpreted as reflecting adaptation in neurons selectively sensitive to the direction of a frequency sweep but was then shown to correspond to only a small change in performance (from 75% to 65%) by Wakefield and Viemeister (1984). Wakefield and Viemeister measured psychometric functions for unadapted and adapted FM up-sweeps and showed that the small difference in performance could be accounted for by a change in decision strategy.

The aim of the present study was to investigate a forward-masking effect in the FM domain and to use a forward-masking paradigm to advance the understanding of the mechanisms underlying FM processing. This technique was chosen over a simultaneous-masking paradigm because for FM with different rates applied simultaneously to the same carrier, spectral masking and beats resulting from the interaction of spectral components within the same auditory filter cannot be separated from any potential masking in the FM domain. Because of that, simultaneous masking cannot be used to investigate whether or not there is FM masking *per se*.

A forward-masking paradigm was deemed appropriate because recent reports showed that an exposure to relatively short (150-ms) AM affects sensitivity to ensuing AM of a similar modulation rate for a period of at least 100 to 200 ms and, in contrast to the results of the earlier long-term adaptation experiments, this “AM forward masking” effect is large and robust even after extensive training (Wojtczak and Viemeister, 2005; Wojtczak *et al.*, 2011). Additionally,

Viemeister *et al.* (2010a) measured psychometric functions for FM detection with and without an FM forward masker, and they found that the shift of the psychometric function due to the masker was large enough to change the performance from nearly perfect to chance. Viemeister *et al.* also showed that the shift in the psychometric function was not as substantial when the signal FM followed a burst of AM.

The current study builds upon these earlier findings by investigating the role of FM-to-AM conversion in the peripheral auditory filters as well as the role of spectral masking in the forward masking of FM. The basic characteristics of FM forward masking are also explored, including rate selectivity and the time course of recovery.

II. EXPERIMENT 1: FM DETECTION WITH FM AND AM FORWARD MASKERS

Due to bandpass filtering on the basilar membrane, the excitation pattern at the output of a single peripheral channel tuned to the carrier frequency of an FM tone exhibits periodic waxing and waning over time. This conversion of FM to AM in the auditory filters has been considered as one of the possible mechanisms underlying FM detection (Zwicker, 1962; Edwards and Viemeister, 1994b). The rate of AM at the output of a filter tuned to the carrier frequency is twice the modulation rate of the FM if one assumes a symmetric filter shape. In reality, this rate can only be considered as an approximation, since the exact rate varies with the asymmetry of the filter. On the other hand, for small frequency deviations, the long-term magnitude spectrum of the FM tone is the same as that for an AM tone with the same carrier frequency and modulation rate. Consequently, the excitation patterns corresponding to the long-term magnitude spectra are identical for the two types of modulation. The present experiment was used to test the hypothesis that forward masking of FM is not simply a result of FM being represented by AM in the auditory system. If the hypothesis is correct then the increase in FM detection thresholds in the presence of a forward masker (relative to those observed without a masker) should be greater when the masker is FM than AM. In contrast, if the forward masking of FM is solely due to forward masking by AM then both types of maskers should produce a similar change in FM detection.

A. Methods

1. Stimuli

The detection of a 100-ms, sinusoidal FM signal (S_{FM}), with a modulation rate of f_m , was measured with three types of forward maskers, FM with a modulation rate of f_m (M_{FM}), AM with a modulation rate of f_m (M_{AM}), and AM with a modulation rate of $2 \cdot f_m$ (M_{2AM}). A schematic illustration of a sample stimulus in the observation interval containing the signal is shown in Fig. 1. Three modulation rates were used for S_{FM} , 5, 20, and 40 Hz. Given the S_{FM} duration, the 5-Hz S_{FM} consisted of only a half-cycle of modulation.

Masked detection thresholds were compared with thresholds measured without the presence of masker modulation. The masker (either AM or FM) and FM signal were

FIG. 1. A schematic illustration of a sample stimulus' instantaneous frequency as a function of time in the signal interval of a 3I-3AFC procedure used to measure FM forward masking. The unmodulated carrier was uninterrupted between the M_{FM} and S_{FM} and extended after the offset of the S_{FM} . In the reference condition (unmasked FM detection) only the S_{FM} was present in the signal interval.

imposed sequentially on a 70-dB SPL, 4-kHz carrier. This carrier frequency was chosen to minimize the role of phase locking in frequency coding (Weiss and Rose, 1988) and to ensure that relatively large frequency deviations in FM could be used. The carrier had a duration of 750 ms including 5-ms raised-cosine, on-off ramps. The masker modulation occupied the initial 500 ms of the carrier and the S_{FM} started 20 ms after the end of the masker. Both the signal and masker modulation started in sine phase. In the measurements of threshold for detecting the unmasked S_{FM} , the temporal position of the S_{FM} within the carrier was the same as when a masker was used.

The M_{FM} was sinusoidal on a linear frequency scale and spanned the frequency range of $\Delta f = \pm 300$ Hz around the carrier frequency. This frequency deviation yielded highly detectable FM and produced substantial changes in excitation level at the output of the filter tuned to the carrier frequency over a period of a modulation cycle. The M_{AM} and M_{2AM} were also sinusoidal with a 100% modulation depth ($m = 1$). The modulated portions of the carrier were given by the following equations:

$$x_{FM}(t) = A \sin[2\pi f_c t + (\Delta f / f_m) \sin(2\pi f_m t)], \quad (1)$$

$$x_{AM}(t) = A[1 + m \sin(2\pi f_m t)] \sin(2\pi f_c t), \quad (2)$$

where A denotes the amplitude of the carrier, f_c is the carrier frequency, f_m is the modulation rate, Δf is the frequency deviation of FM (excursion from the carrier), and m is the modulation index of AM.

2. Procedure and apparatus

The detection of S_{FM} was measured using an adaptive three-interval, three-alternative-forced-choice (3I-3AFC) procedure with a three-down, one-up tracking technique estimating the 79.4% correct point on the underlying psychometric function (Levitt, 1971). Before each new trial, a "ready" light flashed for 250 ms, followed by a 100-ms pause. The observation intervals were separated by 300 ms of silence and were marked by lights on a computer screen. Listeners entered their responses via a computer keyboard and after each trial were given visual feedback indicating the

correct interval. The frequency deviation of the S_{FM} (Δf_s) was initially set to a value for which it was easily detected. Subsequently, Δf_s was varied using multiplicative steps with a factor of 1.3 during the first 4 reversals, and 1.15 during the remaining 8 reversals. These sizes for the multiplicative steps were chosen based on the slopes of the psychometric functions in the study of Viemeister *et al.* (2010a). A run terminated after a total of 12 reversals. Threshold Δf_s was calculated as the geometric mean of the frequency deviations at the final eight reversal points. For each condition, two runs were completed before moving to the next condition. This was repeated until a total of six runs per condition were completed. The order of conditions was chosen pseudo-randomly. Listeners were typically run in 2-h sessions, and multiple sessions were necessary to complete the experiment.

The stimuli were generated digitally via MATLAB (The MathWorks) on a PC equipped with a 24-bit sound card (GINA 3G, Echo Digital Audio) using a 44.1-kHz sampling rate. The stimuli were presented monaurally to the left ear over stereo headphones (MDR-V6, Sony Corporation) with the listeners seated in a sound-attenuating chamber (Industrial Acoustics Company).

3. Listeners

Six listeners (two males, four females) participated in the experiment. One listener was the first author, while the other five were recruited from the undergraduate student population at the University of Minnesota and were paid for their participation. All the listeners had thresholds at or below 15 dB HL at octave frequencies between 250 and 8000 Hz. The listeners received training on a few randomly selected conditions until asymptotic performance was observed. The protocol for all the present experiments was approved by the Institutional Review Board of the University of Minnesota.

B. Results and discussion

The data from individual listeners showed similar trends and thus only the average results (geometric means) are shown for each experiment in this study. Figure 2 shows the mean thresholds for the signal presented without the masker (upper panel) and with the different types of maskers (lower panel). Each bar in the upper panel of Fig. 2 represents the threshold frequency deviation for unmasked S_{FM} , $\Delta f_{s(unn)}$. The thresholds are consistent with those shown in previous studies using a 4-kHz carrier (Moore and Sek, 1996; Viemeister *et al.*, 2010b). A repeated-measures analysis of variance (ANOVA) performed on log-transformed values of $\Delta f_{s(unn)}$ indicated a significant effect of the modulation frequency [$F(2,10) = 13.35$, $p = 0.002$].

The lower panel of Fig. 2 shows the amount of masking in terms of the ratio of frequency deviations observed with and without the masker, $\Delta f_{s(m)}/\Delta f_{s(unn)}$. Differently shaded bars show masking for the three types of maskers used. The M_{FM} produced the largest amount of masking for all modulation rates, increasing the threshold for detecting the S_{FM} by a factor of about 5 on average. This increase was similar to the

FIG. 2. Top panel: Geometric mean frequency deviations for unmasked detection of 5-, 20-, and 40-Hz FM ($\Delta f_{s(unm)}$) for six listeners. Bottom panel: Geometric mean masking ratios, $\Delta f_{s(m)}/\Delta f_{s(unm)}$, for three types of masker modulation: FM and AM with modulation rates equal to the signal rate (M_{FM} and M_{AM}), and AM at double the signal rate (M_{2AM}). Error bars represent the standard error of the geometric means.

threshold change due to the FM forward masker reported by Viemeister *et al.* (2010a). Given the psychometric functions measured by Viemeister *et al.* (2010a), over the range of frequency deviations between the unmasked and masked thresholds, detection performance for the unmasked S_{FM} would be near perfect while masked detection would be at chance.

This large threshold shift was also robust to training. An analysis of the individual data with regard to training effects (not shown here) indicated a small decrease in the amount of forward masking over the first 3 to 6 blocks and no change in performance over a large number of blocks (12 or more) afterward. To further verify the robustness of FM forward masking, thresholds measured in Experiment 1 were retested after the listeners completed all the other experiments within this study. This resulted in at least an additional 25 h of training over a period of 1 to 3 months. There was no significant difference between the thresholds initially measured (after the training period) and those retested at the end of the study. Thus, unlike the effect observed after a long exposure to FM (and AM) in earlier studies of selective adaptation, which may have been due to a lack of training (Moody *et al.*, 1984; Bruckert *et al.*, 2006) or a change in decision strategies (Wakefield and Viemeister, 1984), the FM forward-masking effect is more likely to have a sensory basis.

The two types of masker AM, M_{AM} and M_{2AM} , produced much smaller threshold shifts, by a factor of 2 or less, often corresponding to a marginal change in performance according to the psychometric functions shown by Viemeister *et al.* (2010a). It is not clear whether this effect reflects

AM forward masking due to a partial contribution of FM-to-AM conversion at the output of the auditory filter, or if the threshold shift resulted from other, possibly non-sensory, factors.

A repeated-measures ANOVA performed with the amount of masking (i.e., $\Delta f_{s(m)}/\Delta f_{s(unm)}$) as the dependent variable, pooled across the three modulation rates, showed that the change in threshold due to the presence of a forward masker was statistically significant [$F(3,15) = 87.17$, $p < 0.001$]. *Post hoc* comparisons performed with the Bonferroni correction for multiple comparisons showed that thresholds with any of the three maskers were significantly different from the unmasked thresholds [for M_{FM} : $t(5) = -11.09$, $p < 0.001$; for M_{AM} : $t(5) = -6.65$, $p = 0.001$; and for M_{2AM} : $t(5) = -5.71$, $p = 0.002$]. There was also a significant difference between the M_{FM} and M_{AM} maskers [$t(5) = 11.07$, $p < 0.001$] but no significant difference between the two rates of AM maskers [$t(5) = 2.81$, $p = 0.04$]. An additional repeated-measures ANOVA did not indicate a significant effect of modulation rate on the amount of masking by the M_{FM} [$F(2,10) = 3.50$, $p = 0.07$].

III. EXPERIMENT 2: SPECTRAL FORWARD MASKING AND THE EFFECT OF FM MASKER DEPTH

It is conceivable that the observed FM forward masking effect is spectrally based, i.e., FM detection may result from detection of its (long-term) spectral components, which could be masked by the frequency components of the FM forward masker. Hartmann and Hnath (1982) suggested that detecting FM is based on the detection of the lower sidebands in the magnitude spectrum (see also Goldstein, 1967).

The magnitude spectrum of an FM stimulus depends on the modulation depth of the FM. As the modulation depth increases, the bandwidth of the FM stimulus increases but the magnitudes of the components closest to the carrier decrease, as shown by the three examples for frequency deviations of 33, 300, and 2700 Hz in Fig. 3. Therefore, if spectral masking were involved, FM forward masking should depend on the modulation depth of the masker in a way that could be predicted based on peripheral filtering. Additionally, the forward-masking effect should be determined entirely by the magnitude spectrum and should not depend on the phases of components originating from the M_{FM} .

In this experiment, detection of S_{FM} was measured as a function of the frequency deviation of the M_{FM} . In addition, forward masking by a stimulus with a magnitude spectrum identical to that of the 4-kHz carrier with M_{FM} but the phase spectrum modified by assigning a random phase to each component, was also used. If FM forward masking were spectrally based, thresholds for detecting the S_{FM} would be the same for the M_{FM} and for the randomized-phase FM masker (M_{RPFM}).

A. Methods

Detection of the S_{FM} following a same-rate masker was measured with two types of maskers. For sinusoidal M_{FM} , the detection thresholds were measured as a function of the frequency deviation of the masker. Masker Δf 's of 33, 100,

FIG. 3. The magnitude spectra for a 4-kHz carrier modulated by 20-Hz FM with three different frequency deviations, 33, 300, and 2700 Hz. The scaling of the y-axes is linear and consistent across the panels.

300, 900, and 2700 Hz were used. All the frequency deviations were clearly detectable. For the other type of masker, the sinusoidal M_{FM} was replaced by a M_{RPFM} . Thresholds were measured using the 3I-3AFC procedure described earlier.

The M_{RPFM} was generated independently for each observation interval by applying sinusoidal FM with the desired depth and rate to a 4-kHz carrier, computing the fast Fourier transform (FFT) of the resulting waveform, and replacing the phase of each spectral component by a phase randomly drawn from a rectangular distribution over a range from 0 to 2π . Finally, the M_{RPFM} was reconstructed by computing an inverse FFT of the original magnitude spectrum combined with the new randomized phase spectrum. The root-mean-square amplitude of the M_{RPFM} waveform was then set equal to that of the waveform with sinusoidal M_{FM} to compensate for possible changes in loudness due to the transformation. The resulting noise-like waveform had periodic amplitude fluctuations and additional components in the FM-rate domain. The waveforms and the FM spectra¹ of the 4-kHz carrier modulated by 20-Hz FM and with 20-Hz RPFM are shown in Fig. 4. The two RPFM waveforms (top row) and average modulation spectra (bottom row) in the right columns are for two different Δf 's, 33 and 2700 Hz. Since the exact modulation spectrum of RPFM depends on the choice

of component phases, the modulation spectra in Fig. 4 were obtained by averaging the magnitudes of modulation components for 10 000 realizations of the stimulus.

For the M_{RPFM} conditions only, the 500-ms waveform with the masker was ramped off with a raised cosine over the course of 5 ms at the same time as the 4-kHz carrier was ramped on, to create a smooth transition from the “noisy” masker to the carrier before the S_{FM} was presented. In rare instances the transition was noticeable (e.g., a “click” or a very brief silent gap was perceived), depending on the relative phases at the point of addition of the M_{RPFM} and the 4-kHz waveforms.

The durations of the modulated segments and the masker-signal delay were the same as in Experiment 1. All the remaining experimental details and equipment were also the same.

Five out of the six listeners who participated in Experiment 1 were recruited for this experiment.

B. Results and discussion

Geometric means of masking ratios, $\Delta f_{s(m)}/\Delta f_{s(unn)}$, for the five listeners are shown in Fig. 5 for M_{FM} (filled symbols) and M_{RPFM} (open symbols) with different frequency deviations. For the modulation rates of 5 and 20 Hz (top panels), a change in threshold for detecting the S_{FM} was greater

FIG. 4. Sample waveforms (top row) and the average FM magnitude spectra (footnote 1) (bottom row) of a 4-kHz carrier modulated by 20-Hz FM (left column) and 20-Hz RPFM with two frequency deviations (two right columns). Error bars in the bottom row represent the standard deviation of the mean for 10 000 sample waveforms. The scaling of the y-axes is linear and consistent across the panels within a row.

FIG. 5. Geometric mean masking ratios from five listeners for the FM (M_{FM} , filled symbols) and RPFM masker (M_{RPFM} , open symbols) plotted as a function of the masker's modulation depth (Δf). Different panels show the results from different rates of the signal/masker. Error bars represent standard error of the geometric means.

for M_{FM} than for M_{RPFM} for all masker Δf 's used. This was also true for the 40-Hz rate, except at the two extreme Δf 's. A repeated-measures ANOVA was performed for the dependent variable of masking ratio with the main factors of masker type (M_{FM} , M_{RPFM}) and masker Δf (33, 100, 300, 900, 2700 Hz) pooled across the three modulation rates. The ANOVA showed a significant effect of the masker type [$F(1,4) = 466.82$, $p < 0.001$] and a significant effect of Δf [$F(4,16) = 12.30$, $p < 0.001$]. There was also a significant interaction between the effects of masker type and Δf [$F(4,16) = 8.70$, $p = 0.001$] reflecting the difference in the shape of the masking patterns across Δf 's between the two types of masker.

The results clearly indicate that FM forward masking is not mediated by spectral masking of audio frequencies in the stimuli. Although the M_{RPFM} masker had a much smaller effect on the detection of the signal than the M_{FM} masker, except for the smallest and largest Δf used, the amount of masking it produced was significant. Viemeister *et al.* (2010b) measured thresholds for the detection of random-phase FM (RPFM), also using a 4-kHz carrier, and compared them to thresholds for detecting sinusoidal AM and FM. The comparisons led them to conclude that RPFM is detected using the AM of the stimulus. If AM remained the most prominent feature for the suprathreshold RPFM used in Experiment 2 as a forward masker, then one might expect the amount of masking to be comparable with that observed for M_{AM} in Experiment 1. Indeed, the amount of masking produced by the M_{RPFM} was similar, albeit somewhat larger than that produced by the M_{AM} and M_{2AM} in Experiment 1. It is possible that suprathreshold M_{RPFM} bears a closer perceptual similarity to AM than FM and the masking effect is a manifestation of AM forward masking. Because the envelope of the M_{RPFM} waveform becomes flatter with increasing Δf (see Fig. 4) the amount of masking should diminish as Δf increases. A small trend in this direction is apparent for the

modulation rates of 20 and 40 Hz, but at present, the evidence is not sufficient to determine if AM masking played a role.

To gain some insight into the underlying masking mechanism, the masking ratios for the three modulation rates were replotted in different panels of Fig. 6 as a function of three possible parameters of the M_{FM} , the Δf of the masker, the modulation index $\beta = \Delta f / f_m$, and a simple measure of the speed of the instantaneous frequency sweep,² expressed in Hz/ms, $4 * \Delta f * f_m / 1000$. If one of these parameters is dominating forward masking of the S_{FM} by the M_{FM} , then one might expect to see similar patterns of the masking ratio plotted against that parameter over an overlapping range of the parameter values. For the Δf of the M_{FM} (top left panel), similar patterns of results were observed for the 20- and 40-Hz S_{FM} , although the masking ratio was consistently smaller for the 40-Hz rate. The pattern for the 5-Hz signal is also similar in shape but had a maximum shifted toward somewhat larger Δf values compared to those for the higher modulation rates. For the modulation index β (top right panel), the pattern of results for the three modulation rates are similar in overall shape but are shifted so that the maximum masking occurred at increasing values of β as the modulation rate decreased. For the sweep rate metric (bottom panel), the data for the 5- and 20-Hz rates show similar patterns over the overlapping range of sweep rates but the pattern for the 40-Hz rate shows a larger difference at the lowest sweep rate. Individual results (not shown) exhibit even less consistent patterns for each of the parameters considered. It appears that, of those three parameters, the Δf of the M_{FM} produces the closest matching of masking ratio patterns across the three modulation rates.

IV. EXPERIMENT 3: BASIC CHARACTERISTICS OF FM FORWARD MASKING: RATE SELECTIVITY

The results from Experiment 1 showed that 500-ms FM adversely affects listeners' ability to detect an ensuing

FIG. 6. Geometric mean masking ratios for five listeners (replotted from Fig. 5), plotted as a function of three parameters of the masker FM, the frequency deviation, Δf (top left panel), the modulation index, β (top right panel), and the average instantaneous frequency sweep rate (bottom panel). Error bars represent standard error of the geometric means.

100-ms burst of FM of the same rate and that this FM forward masking is not a manifestation of AM forward masking due to FM-to-AM conversion at the output of an auditory filter tuned to the carrier frequency. Tuning observed in simultaneous (Bacon and Grantham, 1989; Houtgast, 1989) and forward (Wojtczak and Viemeister, 2005) AM masking support the idea of modulation filters broadly tuned to specific ranges of AM rates (Dau *et al.*, 1997a,b; Ewert and Dau, 2000). However, little is known about masking in the FM domain, mainly because changes in the modulation depth of FM are accompanied by changes to the magnitude spectrum of the frequency-modulated stimulus. Experiment 2 showed that in FM forward masking, spectral masking plays at best only a minor role. Viemeister *et al.* (2010a) measured tuning in FM masking for only one carrier (4 kHz) and one modulation frequency (20 Hz). To examine if that tuning remains relatively constant across modulation rates, two additional rates, one lower and one higher than 20 Hz, were used for the 4-kHz carrier. Additionally, tuning was compared for two carrier frequencies using the same modulation rate. Because the forward-masking paradigm precludes interactions between the spectral components resulting from simultaneous modulation of the carrier by the masker and signal FM, this paradigm may be better suited for testing the hypothesis of modulation-rate selective channels in the processing of FM.

A. Methods

Thresholds for detecting the S_{FM} of a fixed rate were measured as a function of the rate of the M_{FM} using the

3I-3AFC procedure described in Experiment 1. Two carrier frequencies were used, 500 Hz and 4 kHz. For the 4-kHz carrier, rate selectivity in FM forward masking was measured for three modulation rates of the S_{FM} , 5, 20, and 40 Hz. For the 500-Hz carrier, only one rate of the S_{FM} , 20 Hz, was used, and rate selectivity was compared for this rate between the two carrier frequencies. The 20-Hz modulation rate was considered to be sufficiently high to preclude the role of phase locking at the two carrier frequencies, based on the data of Moore and Sek (1996). One issue with a comparison across carrier frequencies is that the amount of FM forward masking can vary depending on the carrier frequencies for the same frequency deviation of the M_{FM} . Pilot runs were used to find frequency deviations producing similar amounts of masking in the conditions where the M_{FM} rate was equal to that of the S_{FM} at the two carrier frequencies. Based on those measurements, a constant $\Delta f/f_c$ ratio was used, with a Δf of 300 Hz for the M_{FM} at 4 kHz, and a Δf of 38 Hz for the M_{FM} at 500 Hz.

For each modulation rate of the S_{FM} , masker rates obtained by multiplying the signal rate by 0.05, 0.1, 0.2, 0.4, 0.8, 1, 1.2, 2.4, 4.8, 9.6, and 19.2 were used, with the restriction that the lowest masker rate had to be at least 2 Hz (allowing for encompassing one complete cycle of M_{FM} within the 500-ms duration). All the remaining experimental details and the equipment were the same as in Experiment 1.

The five listeners who participated in Experiment 2 were recruited for this experiment. All five listeners completed the conditions with the 4-kHz carrier but only three of them were available to complete the experiment using the 500-Hz carrier.

B. Results and discussion

Geometric means of masking ratios are plotted in Fig. 7 as a function of the ratio of the M_{FM} rate to the S_{FM} rate to facilitate comparison of rate selectivity across signal S_{FM} rates and across the two carrier frequencies. The left panel shows rate selectivity in FM forward masking measured for the three rates of S_{FM} used with a 4-kHz carrier. The masking ratios were the greatest when the S_{FM} followed the M_{FM} of the same rate. As the difference between the modulation rates increased, the effectiveness of the masker decreased. Thus, rate selectivity of FM forward masking to the signal rate was evident. Consistent with the data from Experiment 1, less masking was observed for the 40-Hz S_{FM} conditions than for the two lower rates. The rate selectivity functions appear similar on a log-frequency scale for the 20- and 40-Hz S_{FM} but the upper side of the masking pattern was somewhat shallower for the 5-Hz rate.

The right panel of Fig. 7 shows masking patterns for the 20-Hz S_{FM} , for two carrier frequencies, 500 Hz (open diamonds) and 4 kHz (shaded triangles). The data for the 4-kHz carrier differ slightly from those shown in the left panel because they are the mean for the subset of three listeners who completed the experiment for both carrier frequencies. As with the 4-kHz carrier, rate selectivity of FM forward masking to the signal rate was observed at 500 Hz. The masking ratio for the 20-Hz M_{FM} was somewhat greater at 500 Hz than at 4 kHz despite the effort to choose masker depths yielding similar amounts of on-frequency masking. Although rate selectivity around the peak of the function appears somewhat sharper for the 500-Hz carrier, if the data are normalized to align the maximum masking ratios, the functions nearly overlap.

It has been suggested that FM detection for low carrier frequencies and low modulation rates (≤ 10 Hz) is at least partially mediated by phase locking to the fine structure of the FM carrier (Moore and Sek, 1996). According to this hypothesis, although the modulation rate of the S_{FM} was too high for phase locking to be involved, some of the masker rates did fall into the range below 10 Hz. Despite that, the rate selectivity on the lower sides of the masking patterns was very similar for the 500-Hz carrier, for which phase locking is robust, and the 4-kHz carrier, for which phase locking is presumably greatly diminished (Weiss and Rose,

1988). However, no conclusions about tuning of FM masking, coded via phase locking to changes in carrier frequency over time, can be drawn based on the present data, since stimuli with a low carrier frequency and modulation rates below 10 Hz, for which this coding strategy may play a role, were not used in this study.

V. EXPERIMENT 4: BASIC CHARACTERISTICS OF FM FORWARD MASKING: RECOVERY

All the experiments thus far have used a fixed delay of 20 ms between the offset of the M_{FM} and onset of the S_{FM} . Experiments 1 and 2 showed that the FM forward masking is not simply a manifestation of AM forward masking, for which the time constant was estimated by Wojtczak and Viemeister (2005), or forward masking of audio frequencies, for which time constants were estimated in numerous studies (e.g., Nelson and Pavlov, 1989). In this experiment, the recovery from FM forward masking was examined.

A. Methods

Detection of the S_{FM} was measured as a function of the delay between the M_{FM} and the S_{FM} using the 3I-3AFC procedure described earlier. The M_{FM} had a frequency deviation of 300 Hz and the modulation rate was equal to that of the signal. Masker-signal delays of 0, 20, 40, 80, 140, 200, 300, and 500 ms were used, and the carrier was uninterrupted between the two bursts of FM, as illustrated in Fig. 1. For the delays up to 140 ms, the carrier had a duration of 750 ms, and thus a varying portion of the unmodulated carrier followed the 100-ms S_{FM} , depending on the delay used. For the longest masker-signal delays, the duration of the carrier was extended so the carrier terminated with the offset of the S_{FM} . All the remaining details of the experimental design and equipment were the same as in the previous experiments.

The five listeners who completed Experiments 2 and 3 also participated in this experiment.

B. Results and discussion

The mean recovery functions for five listeners are shown in Fig. 8. Different symbol types show the masking ratios plotted as a function of the masker-signal delay for different FM rates. A roughly linear recovery from forward

FIG. 7. Geometric mean masking ratios plotted as a function of the ratio of the M_{FM} to S_{FM} rates. Left panel: Data with a 4-kHz carrier from five listeners. Open circles, shaded triangles, and filled squares represent rate-selectivity functions for the 5-, 20-, and 40-Hz S_{FM} rates, respectively. Right panel: Data from three listeners for 20-Hz S_{FM} applied to a 500-Hz carrier (open diamonds) and a 4-kHz carrier (shaded triangles). The error bars represent standard error of the geometric means.

FIG. 8. Geometric mean masking ratios for five listeners, plotted as a function of the masker-signal delay. Open circles, shaded triangles, and filled squares represent recovery functions for the 5-, 20-, and 40-Hz S_{FM} rates, respectively. The break in the functions between 140 and 200 ms represents the transition from a fixed 750-ms stimulus with an unmodulated carrier fringe following the S_{FM} to the carrier being terminated at the end of the S_{FM} . Error bars represent standard error of the geometric means.

masking was observed with delay plotted on a logarithmic scale. The recovery functions were very similar for the three modulation rates used but the amount of forward masking was consistently smaller for the 40-Hz FM than for the two lower rates. The thresholds measured with the carrier ending simultaneously with the S_{FM} (separated by discontinuing the lines connecting the symbols) indicated that the course of recovery was not affected when the unmodulated portion of the carrier following the signal was removed.

A repeated-measures ANOVA was performed for the dependent variable of masking ratio with the main factors of signal/masker rate (5, 20, 40 Hz) and masker-signal delay (0, 20, 40, 80, 140, 200, 300, 500 ms). The ANOVA showed a significant effect of the modulation rate [$F(2,8)=7.15$, $p=0.02$] and a significant effect of delay [$F(7,28)=33.12$, $p<0.001$]. There was not a significant interaction [$F(14,56)=0.67$, $p=0.79$].

Following Wojtczak and Viemeister (2005), an exponential function was fitted to the data to estimate the time of recovery from FM forward masking

$$M(d) = M_0 e^{-d/\tau} + M_{RES}, \quad (3)$$

where $M(d)$ is the amount of masking at delay d , M_{RES} is the residual masking at the asymptote of the function, M_0 is the maximum masking relative to the residual masking, and τ is the time constant describing the rate of recovery. The time constants for the 5-, 20-, and 40-Hz functions were 167.2, 100.3, and 72.2 ms, respectively. (The proportions of variance of the data that was accounted for by the exponential fits were 0.98 for the 5-Hz, 0.95 for 20-Hz, and 0.95 for the 40-Hz FM.) The time constant appears to decrease with increasing modulation rate, especially for the 40-Hz rate. Since masked thresholds also decreased with increasing FM rate, the shorter recovery time at higher rates may be due to a smaller dynamic range, i.e., a smaller difference between

the threshold corresponding to maximum masking and the threshold measured without the masker.

VI. GENERAL DISCUSSION

Despite the fact that FM, like AM, is present in most natural sounds, including speech, masking in the AM domain has received much more attention in auditory research. One reason for the disproportional interest in AM versus FM masking is that changes in the frequency extent of FM are accompanied by changes in the long-term spectrum of an FM stimulus, complicating the interpretation of masking data. In addition, interactions between frequency components that appear in the long-term amplitude spectra as a result of using different FM rates to simultaneously modulate the same carrier would make it hard, if not impossible, to interpret results in terms of FM masking *per se*. Therefore, different paradigms have been used in an attempt to reveal an FM-on-FM effect. One involves the measurement of FM detection interference (FMDI; Wilson *et al.*, 1990; Gockel and Carlyon, 2000). Wilson *et al.* (1990) showed that FM applied to one tonal carrier affected the detection of simultaneous FM at a remote carrier frequency. The patterns showing the amount of FMDI as a function of the rate of the interfering FM showed more than one peak over a relatively small range of modulation rates (2 to 18 Hz around the 6-Hz target FM) or were nearly flat. Although Wilson *et al.* argued that within-channel interactions were not used to detect the target FM, no attempts were made to model the output of peripheral auditory filters to the stimuli used in their experiments to support this statement. Gockel and Carlyon (2000) showed that FMDI can also be observed for sequential presentation of the interferer and target FM, at least when their rates are equal. Although it reached statistical significance, the non-simultaneous FMDI effect was small. In addition, the comparison of thresholds for detecting the target FM obtained from the first and the last three runs showed a substantial decrease of non-simultaneous FMDI with training.

Another experimental paradigm used to demonstrate masking-like effects in the FM domain involved measuring FM detection after a long exposure to the same-rate FM (Kay and Matthews, 1972; Regan and Tansley, 1979; Tansley and Suffield, 1983). Although the increase in FM detection thresholds due to the long exposure was initially interpreted as reflecting FM specific adaptation, later studies presented evidence undermining this interpretation. Re-examination of the “adaptation” effects revealed that the threshold elevation can be eliminated by training (Moody *et al.*, 1984) and that the change in threshold translates to a small change in performance and can be accounted for by non-sensory factors, such as a change in the decision strategy (Wakefield and Viemeister, 1984).

In contrast, in this study a large change in performance was observed after an exposure to just a 500-ms burst of FM. The effect was robust even after extensive training and is therefore likely to have a sensory basis. The effect was not due to FM-to-AM conversion or spectral masking and appeared to be specific to FM. The main difference between this study and the early studies of adaptation to FM was in

the duration of the stimuli. Almost all of the early studies (e.g., [Tansley and Suffield, 1983](#)) used signals with durations of several seconds. Assuming that the long-duration modulators used as adaptors in these early studies produced forward masking with recovery times similar to those shown in Fig. 8 (i.e., on the order of 100 to 200 ms), no effect of this forward masking on the detection of the signal would be expected for signal durations of several seconds. The only exceptions were the studies by [Gardner and Wilson \(1979\)](#) and [Wakefield and Viemeister \(1984\)](#), which used FM sweeps shorter than the 100-ms S_{FM} used in the present experiments. However, the paradigm implemented by those authors involved a two-alternative forced choice task, with two observation intervals separated by a 500-ms silent gap, following the end of the adaptor. With such a long silent gap, full recovery from exposure to the adaptor might have occurred before the onset of the signal in trials with the signal presented in the second interval. Although the masking observed in the present experiments may reflect adaptation of responses to FM in neurons that are selectively sensitive to FM characteristics (e.g., FM rate), it is premature to speculate about the specific mechanism underlying the effect and the present study has simply referred to it as FM forward masking.

As mentioned in Sec. I, an important question investigated by previous studies was whether a common mechanism underlies the detection of AM and FM or whether FM is detected via at least a partially independent mechanism ([Edwards and Viemeister, 1994a,b](#); [Moore and Sek, 1995, 1996](#)). When AM was used as a forward masker of FM, a small but statistically significant increase in threshold was observed in Experiment 1. Given the psychometric functions measured by [Viemeister et al. \(2010a\)](#), the threshold shift caused by exposure to AM corresponded to a relatively small change in performance. This threshold shift could either be a manifestation of AM forward masking due to FM-to-AM conversion of the modulation in the filter tuned to the carrier, or it could simply reflect a change in decision strategy resulting from a listener's difficulty to ignore the fluctuating masker (see [Wakefield and Viemeister, 1984](#)). However, the FM masker produced a substantially larger shift in threshold for all three modulation rates used and was not accounted for by masking of audio frequencies due to the overlap in the spectra of the 4-kHz carrier with the M_{FM} and S_{FM} . This result suggests that there is a strong component of FM processing that is independent of AM processing. In contrast to the studies by [Moore and Sek \(1992, 1996\)](#), the use of a 4-kHz carrier in this study made phase locking to the changes in carrier frequency an unlikely candidate for the independent mechanism involved in FM but not AM coding. Although the experiments conducted within this study were not designed to elucidate a specific mechanism underlying selective FM processing, the feature-selective neural channels must receive inputs from peripheral sites that are different for the two types of modulation. One possibility is that AM channels respond to within-channel changes in excitation level in the auditory periphery, while FM channels (in addition) respond to asynchrony of changes in excitation level across adjacent peripheral channels. The rate selectivity of FM forward

masking observed in Experiment 3 suggests modulation-rate selective processing of FM.

A few physiological studies have found cortical neurons that exhibited a sustained response to FM tones but not to steady tones ([Whitfield and Evans, 1965](#) in awake cats; [Atencio et al., 2007](#) in awake owl monkeys; [Qin et al., 2008](#) in awake cats) possibly suggesting the existence of a high-level mechanism that specializes in FM processing. [Qin et al. \(2008\)](#) suggested that different populations of cortical neurons specialize in the coding of different characteristics of FM stimuli, such as frequency extent, speed (i.e., sweep rate), and the direction of the frequency sweep. In Experiment 2 some of those characteristics were considered by plotting the amount of forward masking as a function of Δf and the sweep rate of the masker (Fig. 6). The closest similarity between the masking patterns of the three modulation rates used was observed when masking ratios were plotted as a function of masker Δf , with the maximum masking roughly corresponding to $\Delta f = 300$ Hz. It would be premature to draw strong conclusions regarding the role of the frequency extent in FM coding based on these data but given the physiological results from experimental animals (e.g., [Qin et al., 2008](#)), this Δf may represent the boundary of the tonal receptive field for neurons tuned to 4 kHz (the carrier frequency) in the auditory cortex of humans.

When plotted on a log-frequency scale, rate selectivity of FM forward masking was very similar across the modulation rates and carrier frequencies used, as shown in Fig. 7. The time course of recovery from FM forward masking was also similar (Fig. 8). Overall, the results are consistent with a hypothesis that FM forward masking is processed by modulation-rate selective neurons whose response adapts and recovers slowly over the course of 100 to 200 ms. Although there is some physiological evidence for a similar hypothesis considered by [Wojtczak and Viemeister \(2005\)](#) regarding AM processing ([Bartlett and Wang, 2005, 2007](#)) there appears to be no physiological studies that measured changes in neural responses after an exposure to FM.

At present, it is not clear to what extent the observed FM forward masking affects processing of natural sounds. Since FM plays an important role in the perception of speech (e.g., [Zeng et al., 2005](#)), it is desirable to examine the role of the effects demonstrated in this study in practical listening situations.

VII. SUMMARY AND CONCLUSIONS

- (1) An on-frequency FM forward masker produces a substantial reduction in sensitivity to subsequent FM, similar to forward masking of auditory frequencies. The forward masking effect is not merely a manifestation of AM forward masking due to FM-to-AM conversion (Fig. 2) or a manifestation of forward masking of audio-frequency components (Fig. 5).
- (2) The amount of FM forward masking shows a nonmonotonic dependence on the masker frequency deviation, modulation index, and sweep rate (Fig. 6). For each of these masker characteristics, the masking patterns

exhibit a peak, and the patterns measured for different FM rates are similar when plotted as a function of the masker frequency deviation.

- (3) FM forward masking exhibits relatively broad rate selectivity that appears roughly similar on a log-frequency scale across S_{FM} rates and carrier frequencies (Fig. 7).
- (4) Recovery from FM forward masking is well described by an exponential function with a time constant between 72 and 167 ms, for the three modulation rates used in this study (Fig. 8).
- (5) The characteristics of FM forward masking are similar to those for AM forward masking, and for forward masking of audio frequencies, suggesting the possibility that FM is processed in modulation-rate selective channels that adapt and recover over the course of a few hundred milliseconds.

ACKNOWLEDGMENTS

This work was supported by Research Grant No. R01 DC 00683 from the National Institute on Deafness and Communication Disorders, National Institutes of Health. M.W. was supported by Grant No. R01 DC 010374 from the National Institutes of Health while working on this manuscript. The authors thank two anonymous reviewers for their helpful comments of the earlier version of the manuscript.

¹The “FM spectra” refers to the spectrum obtained from taking the FFT of the instantaneous frequency (as a function of time) after taking the time derivative of the instantaneous phase of the analytic version of the masker waveform.

²The speed was defined as the frequency range traveled within a period corresponding to one modulation cycle. Since the deviation Δf is traveled four times over one modulation cycle and the period expressed in milliseconds is equal to $1000/(1/f_m)$, the speed expressed in Hz/ms is the ratio of the frequency range to the time over which that range was traveled, resulting in $4 \cdot \Delta f \cdot f_m / 1000$.

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