The effects of unmodulated carrier fringes on the detection of frequency modulation

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Detection thresholds for 100 ms of either 5- or 20-Hz frequency modulation (FM) were measured at various temporal positions within a 600-ms, 4-kHz pure-tone carrier. The results indicated that the temporal position of the signal relative to the fringe influences detection thresholds, including an effect that is reminiscent of auditory backward recognition masking. A task involving frequency increments, rather than sinusoidal FM, yielded similar results. Additional manipulation of total carrier duration indicated that FM detection thresholds improve as the duration of the forward fringe increases, while a backward fringe only degrades performance in the absence of any forward fringe. The results suggest that listeners are insensitive to subtle frequency changes that occur at the onset of a longer stimulus and that the interaction between the opposing effects of the forward and backward fringes is not additive. © 2013 Acoustical Society of America.
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I. INTRODUCTION

Detection of amplitude modulation (AM) by human listeners can be improved when the modulation to be detected is preceded or followed by an unmodulated temporal fringe (e.g., for broadband-noise carriers; [Sheft and Yost, 1990, 1995](#)) and is typically explained by way of models that integrate intensity over time (e.g., [Sheft and Yost, 1990](#)). The present experiments address the question of whether an unmodulated fringe also affects the detection of frequency modulation (FM), without such intensity changes, and its implications on how frequency changes are perceived.

Of the various accounts for the detection of FM, one explanation is “FM-to-AM conversion” (e.g., [Zwicker, 1962](#)). This explanation posits that as instantaneous frequency changes, the output of an auditory filter will fluctuate as the frequency sweeps through the passband of the filter, resulting in an AM-like output. If FM is detected in this manner, adding an unmodulated fringe around the FM signal may improve thresholds in a way that is similar to what is observed with AM signals ([Sheft and Yost, 1990, 1995](#)).

Another account for FM detection, which has been shown to apply to detection at low modulation frequencies (below 6 Hz), is that the instantaneous frequency of the FM waveform is sampled, and discrimination of an average deviation from the carrier frequency mediates detection of FM ([Hartmann and Klein, 1980](#)). This model accounts for the fact that frequency-difference limens measured with fixed-frequency pure tones are smaller than those for comparable FM detection tasks (e.g., [Fastl, 1978](#)) because the average deviation of the dynamic FM is less than its maximum deviation from the carrier. Thus the excursion from the carrier of an FM signal must be larger for that sampled average

to equal that of a smaller difference limen using a fixed-frequency tone.

Because FM detection and frequency discrimination are mediated by a common mechanism, one would expect comparable effects of temporal fringes on FM detection and frequency discrimination thresholds. In frequency discrimination, the inclusion of a backward fringe can create a masking effect that has been called auditory backward recognition masking (ABRM; e.g., [Massaro, 1975](#); [Kallman and Massaro, 1983](#)), while a forward fringe either has no effect ([Leshowitz and Cudahy, 1973](#)) or slightly improves discrimination ([Ronken, 1972](#)). Explanations of ABRM have typically involved short-term memory and the encoding of the initial tone being disrupted by the tone that follows (e.g., [Massaro, 1975](#); [Kallman and Massaro, 1983](#)). [Other research ([Sparks, 1976](#)) has indicated that the ABRM effect is better labeled as “interference” than as “masking” given the cognitive explanation of the empirical results.]

If similar issues occur with FM detection, unmodulated fringes could potentially influence experiments that are attempting to measure other types of effects. Recently, [Byrne et al. \(2012\)](#) measured FM detection following a variety of modulated forward maskers. The FM to be detected was temporally embedded within a longer-duration uninterrupted pure-tone carrier, which resulted in portions of unmodulated carrier surrounding the FM signal. Using these stimuli, [Byrne et al.](#) manipulated the duration of the unmodulated portions while measuring recovery from the effects of FM forward maskers. As the masker-signal delay increased, forward masking decreased; however, the durations of the unmodulated portions, both preceding and following the signal, were varied along with the masker-signal delay, precluding separation of any possible effects of fringe duration from the recovery from FM forward masking.

Using stimuli similar to [Byrne et al. \(2012\)](#), the present experiments not only investigate the effect of the temporal position of a sinusoidal FM signal within an unmodulated

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carrier but also the effect on detection of an increment in frequency from the carrier. The durations of the forward and backward fringes are then manipulated independently to better describe the effects.

II. EXPERIMENT 1: FRINGE EFFECTS ON FM AND FREQUENCY INCREMENT (FI) DETECTION

This experiment examined the effect of an unmodulated temporal fringe on the detection of changes in instantaneous frequency. Because FM detection can be interpreted as a form of frequency discrimination, a backward fringe is expected to cause masking (i.e., ABRM) while a forward fringe is not, as has been shown for frequency discrimination. However, if another mechanism is driving FM detection, such as FM-to-AM conversion, a backward fringe may not degrade thresholds.

For comparison, fixed-frequency-discrimination thresholds were also measured. When temporal fringes of the standard frequency are added to a frequency-discrimination stimulus, the task becomes a frequency-increment (FI) detection paradigm. This FI detection task is also equivalent to detection of one positive half-cycle of square-wave FM and raises the question of how a fringe will affect frequency difference limens. Moore (1976) compared subject variability in both FM detection and frequency discrimination tasks and found evidence that the ability to detect the two types of frequency changes may be somewhat independent. If that is the case, then the FI signal could be detected as FM due to the brief frequency sweeps present or simply as a comparison of the steady-state frequency portions of the interval (i.e., within-interval frequency discrimination), in addition to a comparison between the two intervals.

A. Methods

Experiment 1 examined the ability to detect a change in frequency (the “signal”) of a 70-dB-SPL, 4-kHz pure tone carrier (f_c). Detection thresholds were measured in a two-alternative, forced-choice task for a signal with a duration of 100 ms at various temporal positions within a 600-ms carrier. The signal was either sinusoidal FM with a modulation frequency (f_m) of 5 or 20 Hz and depth Δf (peak frequency excursion from the carrier) imposed on a 4-kHz carrier or an increment in frequency of Δf from the carrier. These parameters were chosen to be consistent with those of Byrne *et al.* (2012).

As illustrated in Fig. 1, the 5-Hz sinusoidal FM stimulus (middle row) is merely a rounded version of the FI stimulus (top row). (Based on a direct comparison of the two stimuli, the two waveforms were easily discriminable by all listeners at suprathreshold levels.) The FM signal was defined by Eq. (1). The modulator always started in sine phase and, given the modulation rates and duration, began and ended at the carrier frequency

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

A signal interval contained either FM or an FI, in separate conditions, while in the non-signal interval, the stimulus was a

FIG. 1. Instantaneous frequency as a function of time for FI detection (top row), and 5- and 20-Hz FM detection (middle and bottom rows, respectively). The three types of 100-ms signals are centered within the 600-ms carrier and are shown with the same Δf value, i.e., the maximum excursion from the carrier frequency.

4-kHz pure tone. The temporal portion of the stimulus that might contain the signal was always 100 ms in duration. The signal was presented with unmodulated forward fringe durations (T_{FWD}) of 0, 125, 250, 375, and 500 ms and backward fringe durations (T_{BWD}) of $500 - T_{FWD}$, such that the sum of the forward and backward fringe durations was fixed at 500 ms. Thus a $T_{FWD} = 0$ ms condition had no forward fringe and a 500-ms backward fringe, while a $T_{FWD} = 500$ ms condition contained no backward fringe. The signal was temporally contiguous with the fringes (i.e., the signal portion was not gated into a separate segment). For the FI conditions, this was achieved using 5-ms, half-cycle, raised-cosine on/off ramps in the frequency domain to eliminate audible clicks. Additional conditions were run with no temporal fringes in which the duration of each interval was 100 ms. Within each interval, the total stimulus was windowed with 10-ms, half-cycle, raised-cosine on/off ramps, and the silent duration between intervals was 500 ms.

A two-down, one-up tracking procedure in which Δf was varied adaptively using geometric step sizes was used to estimate the 70.7% correct point of the listener’s underlying psychometric function (Levitt, 1971). A block terminated after 12 reversals, and the geometric mean of the Δf values at the final eight reversals was defined as threshold. For the first four reversals, Δf increased or decreased by a factor of 1.32, which was reduced to 1.15 for the final eight reversals. The initial value of Δf was set above the expected threshold

so that the signal would be well detectable at the start of each block of trials.

The listeners were instructed to choose the interval containing a frequency change from the carrier, and the nature of these changes was described using illustrations similar to Fig. 1. The listener initiated each block of trials, and each trial began with a “ready” light followed by a 100-ms pause. Lights marked the listening intervals only during the portions of the stimuli that might have included the signal. The listener entered responses on a keyboard, and correct interval feedback was given. Listeners typically ran in 2-h sessions, and the order in which conditions were run was different for each listener. A condition was complete after a total of four blocks, and the geometric mean of those four threshold estimates was defined as the final threshold for that condition.

Five listeners participated in the experiment (two male and three female). One was the first author, while the others were students and staff from the University of Minnesota who were paid to participate. All listeners had normal hearing based on pure-tone thresholds of 15 dB HL or better at octave frequencies from 250 to 8000 Hz, and all were highly trained in the present, as well as other, psychoacoustical tasks.

Listeners were run individually in a sound-attenuating chamber (Industrial Acoustics Company). The stimuli were generated digitally in MATLAB (The MathWorks) on a personal computer equipped with a 24-bit sound card (GINA 3 G, Echo Digital Audio) and were presented over stereo headphones (MDR-V6, Sony) to only the listener’s left ear.

B. Results and discussion

The general trend of the individual listeners’ results was well captured by the geometric means and standard errors across listeners, which are shown in Fig. 2. (All averages that follow are geometric means, and all statistics were computed on log-transformed values of Δf .) When no fringes were present, the mean Δf threshold for FI detection (frequency discrimination) was better than the thresholds for the two FM

FIG. 2. Geometric mean thresholds in terms of Δf (Hz) across five listeners for FI (closed squares), 5-Hz FM (shaded triangles), and 20-Hz FM detection (open circles) as a function of the position (in terms of forward fringe duration, T_{FWD}) of the 100-ms signal portion relative to the 600-ms total carrier. The left-hand points are for no-fringe conditions, where FI detection is equivalent to frequency discrimination. Error bars represent the standard error of the mean.

rates, which were quite similar despite the 5-Hz modulation covering only half the frequency range of the 20-Hz modulation at a given Δf value. The threshold ranges for the individual listeners were consistent with those of previous research (e.g., for 4-kHz frequency discrimination; Fastl, 1978; for 5- and 20-Hz FM detection; Byrne *et al.* 2012; Viemeister *et al.*, 2010) as well as the trend between conditions (Fastl, 1978).

With fringes included, the FM and FI detection functions generally had the same shape, and the Δf thresholds were similar. A 3×5 repeated measures analysis of variance (ANOVA) was performed for the dependent variable of detection threshold with the factors of signal type (FI, 5-Hz FM, and 20-Hz FM) and forward-fringe duration (0, 125, 250, 375, and 500 ms). There was not a significant difference between signal types, $F(2,8) = 2.34$, $p = 0.16$, but the effect of forward-fringe duration was significant, $F(4,16) = 48.55$, $p < 0.001$. There was no significant interaction, $F(8,32) = 2.17$, $p = 0.06$.

Because the 20-Hz FM contained two full cycles of modulation, while the 5-Hz FM consisted of only the positive half-cycle of the sine wave, the FM functions were also analyzed based on the total frequency excursion (TFE, $2 * \Delta f$). This metric, however, only served to raise the 20-Hz function relative to the other signal types and clearly did not align the functions better than the Δf values plotted in Fig. 3. Although TFE is sometimes used to describe the results of FM experiments (e.g., Viemeister *et al.*, 2010), Δf has typically been used for comparison of FM detection and frequency discrimination (e.g., Fastl, 1978), and the present

FIG. 3. Geometric mean thresholds in terms of the ratio of the with- and without-fringe conditions across four listeners for 5-FM detection (top row) and across five listeners for 20-Hz FM detection (bottom row). Open circles represent conditions when the forward fringe duration varies, while filled circles are for when the backward fringe is manipulated. Left column: Forward-fringe-only and backward-fringe-only conditions as a function of fringe duration. Right column: One fringe is fixed at 500 ms, while the other fringe duration is the x-axis value. Error bars represent the standard error of the mean.

results suggest that Δf is the preferred metric for these types of paradigms.

Performance was degraded for both FM and FI detection when only a backward fringe was included, consistent with the standard ABRM paradigm, despite using signals with a duration much longer than the 10–20 ms typically used in ABRM studies (e.g., Foyle and Watson, 1984). FI detection thresholds were 3.10 times greater, and FM detection thresholds were 1.96 and 1.43 times greater (5- and 20-Hz FM, respectively) with a 500-ms backward fringe than without fringes. That effect was substantially reduced when a forward fringe was included. The 500-ms forward fringe actually improved detection thresholds somewhat for FM relative to when no fringes were present, a result similar to the AM findings of Sheft and Yost (1995). However, because the overall trend of the results was dissimilar to that for AM, the role of an FM-to-AM conversion mechanism was not supported by the present experiment.

Post hoc comparisons performed with the Bonferroni correction for multiple comparisons confirmed that the ABRM effect of the 500-ms backward fringe was significant for all three signal types [FI: $t(4) = -5.43$, $p = 0.003$; 5-Hz FM: $t(4) = -4.76$, $p = 0.005$; 20-Hz FM: $t(4) = -7.47$, $p = 0.001$]. The direction of the effect from the 500-ms forward fringe, however, was mixed. For FI, performance was worse [$t(4) = -4.01$, $p = 0.008$] in contrast to the results of Ronken (1972) using shorter duration stimuli. For 20-Hz FM, performance was significantly better [$t(4) = 5.01$, $p = 0.004$], but the benefit of the forward fringe was not statistically significant for the 5-Hz FM signal [$t(4) = 3.14$, $p = 0.018$]. Because the with-fringe thresholds were similar across signal types, these differing trends for FM and FI were attributable to differences between the no-fringe thresholds. The similarity between thresholds of the with-fringe conditions across the FI and FM signals may indicate that the threshold difference that was observed between frequency discrimination and FM detection can be eliminated, or at least reduced, with the addition of the standard-frequency/unmodulated-carrier fringe. The fringes may make the FI more perceptually similar to FM than to steady-state frequency comparisons and therefore result in different processing strategies (e.g., Moore, 1976) for FI with fringes than without.

What is clear is that there is an obvious effect from the sequential order of the signal and the unmodulated fringe. Although this may be inconsistent with the original Hartmann and Klein (1980) model, a modification of the model, with the sampling window including part of the fringe, could account for the results. If the fringe is included in the frequency deviation estimate, the steady-state frequency during the increment may no longer provide a substantial benefit over the varying FM signal if the duration of that window is greater than that of the signal. In addition, a frequency-sampling window that is asymmetric in shape (with later temporal information given greater weight) could explain the differential effects of forward-only and backward-only fringes.

Performance in the present task was stable after 4–6 h of practice and then remained asymptotic during the final data

collection. There is evidence that more extensive training (30 h or greater) can significantly reduce or eliminate an ABRM effect (Sparks, 1976). The fact that the threshold frequency deviation for the backward-only fringe was twice as large as that for the forward-only fringe highlights the importance of taking these sequential effects into account when designing FM detection experiments using both modulated and unmodulated portions.

III. EXPERIMENT 2: THE INTERACTION BETWEEN FORWARD AND BACKWARD FRINGES ON FM DETECTION

Holding the total carrier duration constant in Experiment 1 made it impossible to evaluate the independent effects of the forward and backward fringes and how they might interact, because the sum of the fringe durations was fixed at 500 ms. By adding a forward fringe, the backward fringe was reduced, so the improvement in thresholds that was seen could have arisen from manipulation of either fringe or a combination of the two. The second experiment manipulated the fringes independently to better describe their effects on FM detection.

Based on the results of Experiment 1, having, and increasing the duration of, only a backward fringe should degrade thresholds, while the opposite should be true with only forward fringes. However, when using a combination of both fringes, the results of these two opposing effects are difficult to predict from the results of Experiment 1 alone. The magnitudes of the positive and negative effects may simply add, or a more complex interaction may be present.

A. Methods

The general method was the same as for Experiment 1 although in this experiment, the fringe durations were varied independently and only FM detection thresholds were measured. In addition to the no-fringe conditions, separate conditions were run with forward fringe durations (T_{FWD}) of 63, 125, 250, and 500 ms with no backward fringe as well as with the same durations for backward fringes (T_{BWD}) without forward fringes. Conditions were also run with the same set of durations for either the forward or backward fringe with the duration of the remaining fringe fixed at 500 ms. All five listeners from Experiment 1 ran the 20-Hz FM conditions, but only four of those listeners were available to run in the 5-Hz FM conditions.

B. Results and discussion

The trends of the mean data across listeners were quite similar for the two FM rates. The left column of Fig. 3 shows that the effect of a fringe on FM detection in terms of the ratio of thresholds for the with-and without-fringe conditions, increases with increasing fringe duration. As in Experiment 1, for a forward fringe, that effect is an improvement in thresholds. With a 500-ms forward fringe, thresholds are improved by a factor of 1.41 (s.e. = 1.15) relative to the no-fringe condition for the 5-Hz signal and by a factor of 1.35 (s.e. = 1.06) for the 20-Hz signal. In contrast, with backward fringes,

thresholds increase with increasing backward fringe duration (an ABRM-like effect) with the thresholds degraded by a factor of 2.13 (s.e. = 1.16) and 1.43 (s.e. = 1.05) with a 500-ms fringe following the signal.

The only noteworthy difference between the 5- and 20-Hz FM functions is that, in the left-hand panels of Fig. 3, the 5-Hz conditions with 63-ms fringes show slightly worse thresholds than without fringes, while the comparable 20-Hz conditions show no effect from that fringe duration. This could indicate that for the 63-ms forward fringe, there is a small benefit of the two full cycles of 20-Hz modulation compared to only the half-cycle of the 5-Hz modulated signal.

The right column of Fig. 3 shows the results of fixing one fringe at 500 ms, while adjusting the other fringe duration. For both FM rates, with a fixed 500-ms forward fringe, varying the backward fringe duration had very little effect. The standard ABRM explanation would not seem to account for this result. In contrast, with a 500-ms backward fringe, the forward fringe duration has a substantial effect. The masking that results from a backward-only fringe is substantially reduced with only a 63-ms forward fringe, and thresholds improve as the duration of the forward fringe is increased. The 63-ms forward fringe alone (Fig. 3, left column) has no substantial effect relative to the no-fringe condition, yet it reduces the masking of the 500-ms backward fringe. It appears as if the backward fringe does not do a fixed amount of masking that the forward fringe opposes but rather that the masking effect is no longer present once the forward fringe is added.

For each FM rate, a 2×5 repeated measures ANOVA was performed for the dependent variable of fringe effect ratio with the factors of fixed fringe type (forward vs backward) and the variable fringe duration (0, 63, 125, 250, and 500 ms). For the 5-Hz FM signal, there were significant effects of fixed fringe type, $F(1,3) = 54.38$, $p = 0.005$ and total fringe duration, $F(4,12) = 19.05$, $p < 0.001$, and there was a significant interaction, $F(4,12) = 12.43$, $p < 0.001$. The same results were seen for the 20-Hz FM signal [fixed fringe type, $F(1,4) = 98.72$, $p = 0.001$; total fringe duration, $F(4,16) = 26.19$, $p < 0.001$; interaction, $F(4,16) = 31.09$, $p < 0.001$].

IV. GENERAL DISCUSSION

The detection of changes in frequency is affected by the temporal position of those changes within an unmodulated carrier. Relative to no-fringe conditions, both FM and FI detection show an ABRM-like effect with only a backward fringe, possibly because the fringe interferes with the encoding of the onset (i.e., the signal portion) of the total stimulus, the ABRM explanation. However, with a forward fringe included, the detection of FM improves. The beneficial effect of the forward fringe could indicate sharper tuning of a (4-kHz) auditory filter after the onset of the stimulus (e.g., Bacon and Viemeister, 1985) or improved detection of dynamic signals following short-term adaptation to steady-state stimuli (similar to auditory adaptation in the inferior colliculus of cats; Kvale and Schreiner, 2004). Ronken

(1972) also posited that improvement in frequency discrimination following presentation of a pure tone could be from a stronger frequency representation (or narrower “frequency contours”; Elliott, 1967) that develop after presentation of a steady-state tone. Therefore the longer the duration of the forward fringe, the better the listener is able to detect a subtle change from the carrier frequency.

The two opposing effects of forward and backward fringes do not appear to simply be additive. By combining the FM detection data from Experiments 1 and 2 (a total of 19 different conditions for each modulation rate) and analyzing the effect of forward or backward fringe duration separately, thresholds were found to be much more highly correlated with forward-fringe duration (r^2 values of 0.83 and 0.86) than with backward-fringe duration (r^2 values of 0.03 and 0.02). As illustrated in the lower panel of Fig. 4, performance cannot be predicted by the backward fringe duration alone. Thresholds with no backward fringe fall within the large range of values with the full 500-ms backward fringe. Forward fringe duration, however, seems to be a very good predictor of performance (top panel), regardless of any influence, or interaction, a backward fringe may have.

The presence of the forward fringe produces an improvement in FM detection thresholds that is seemingly independent from the masking of the backward fringe, and the forward fringe duration determines thresholds overall. The ABRM-like effect seen with FM detection does not

FIG. 4. FM detection data (from both Experiments 1 and 2) replotted as a function of forward-fringe duration (top panel) and also as a function of backward-fringe duration (bottom panel). The correlations for the 5-Hz (shaded triangles, mean of four listeners) and 20-Hz (open circles, five listeners) data are shown within each panel. Error bars represent the standard error of the mean.

appear to be *reduced* by the effect of a forward fringe; it is simply not present when a forward fringe is included. This interpretation is generally consistent with the findings of Nábelek *et al.* (1970), who found evidence that the initial portions of a stimulus are given less weight than later portions when determining the overall pitch. In Nábelek *et al.*, when a frequency glide was presented before a steady-state tone, it did not alter the perception of the pitch of the total stimulus nearly as much as when the glide occurred at the offset.

As noted earlier, these fringe effects could influence the results of other FM paradigms. The FM forward masking recovery functions of Byrne *et al.* (2012) used masker-signal delays that covaried with the durations of unmodulated portions that preceded and followed the FM signal. The magnitude of the unmodulated fringe effect in the present experiment (backward-only fringe thresholds two to three times greater than with only a forward fringe) is less than the effect of the FM forward masker (masked thresholds as much as six times greater than unmasked) seen by Byrne *et al.*; however, the manipulation of unmodulated fringe duration while measuring forward masking recovery could have contributed to a portion of that effect. As the masker-signal delay increased and forward masking was reduced, the unmodulated fringe preceding the signal also increased and could have improved detection as well.

In summary, detection of an FM signal is affected by its temporal position relative to unmodulated portions of its carrier. An ABRM-like effect is observed when the signal precedes an unmodulated backward fringe, similar to that seen for frequency discrimination, while a forward fringe can improve signal detection. Finally, although there is an interaction between the effects of the forward and backward fringes, the duration of the unmodulated forward fringe is the best predictor of the detectability of FM.

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- Bacon, S. P., and Viemeister, N. F. (1985). "The temporal course of simultaneous tone-on-tone masking," *J. Acoust. Soc. Am.* **78**, 1231–1235.
- Byrne, A. J., Wojtczak, M., and Viemeister, N. F. (2012). "Forward masking of frequency modulation," *J. Acoust. Soc. Am.* **132**, 3375–3386.
- Elliott, L. L. (1967). "Development of auditory narrow-band frequency contours," *J. Acoust. Soc. Am.* **42**, 143–153.
- Fastl, H. (1978). "Frequency discrimination for pulsed versus modulated tones," *J. Acoust. Soc. Am.* **63**, 275–277.
- Foyle, D. C., and Watson, C. S. (1984). "Stimulus-based versus performance-based measurement of auditory backward recognition masking," *Percept. Psychophys.* **36**, 515–522.
- Hartmann, W. M., and Klein, M. A. (1980). "Theory of frequency modulation detection for low modulation frequencies," *J. Acoust. Soc. Am.* **67**, 935–946.
- Kallman, H. J., and Massaro, D. W. (1983). "Backward masking, the suffix effect, and preperceptual storage," *J. Exp. Psychol. Learn. Mem. Cogn.* **9**, 312–327.
- Kvale, M. N., and Schreiner, C. E. (2004). "Short-term adaptation of auditory receptive fields to dynamic stimuli," *J. Neurophysiol.* **91**, 604–612.
- Leshowitz, B., and Cudahy, E. (1973). "Frequency discrimination in the presence of another tone," *J. Acoust. Soc. Am.* **54**, 882–887.
- Levitt, H. (1971). "Transformed up-down methods in psychoacoustics," *J. Acoust. Soc. Am.* **49**, 467–477.
- Massaro, D. W. (1975). "Backward recognition masking," *J. Acoust. Soc. Am.* **58**, 1059–1065.
- Moore, B. C. J. (1976). "Comparison of frequency DL's for pulsed tones and modulated tones," *Br. J. Aud.* **10**, 17–20.
- Nábelek, I. V., Nábelek, A. K., and Hirsh, I. J. (1970). "Pitch of tone bursts of changing frequency," *J. Acoust. Soc. Am.* **48**, 536–553.
- Ronken, D. A. (1972). "Changes in frequency discrimination caused by leading and trailing tones," *J. Acoust. Soc. Am.* **51**, 1947–1950.
- Sheft, S., and Yost, W. A. (1990). "Temporal integration in amplitude modulation detection," *J. Acoust. Soc. Am.* **88**, 796–805.
- Sheft, S., and Yost, W. A. (1995). "Temporal masking of amplitude modulation detection with a wideband noise carrier," *J. Acoust. Soc. Am.* **98**, 2907.
- Sparks, D. W. (1976). "Temporal recognition masking—or interference?" *J. Acoust. Soc. Am.* **60**, 1347–1353.
- Viemeister, N. F., Stellmack, M. A., and Byrne, A. J. (2010). "Detection of modulation of a 4-kHz carrier," *J. Acoust. Soc. Am.* **128**, 1578–1581.
- Zwicker, E. (1962). "Direct comparisons between the sensations produced by frequency modulation and amplitude modulation," *J. Acoust. Soc. Am.* **34**, 1425–1430.