Cross-Modulation Interference With Lateralization of Mixed-Modulated Waveforms

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Purpose: This study investigated the ability to use spatial information in mixed-modulated (MM) sounds containing concurrent frequency-modulated (FM) and amplitude-modulated (AM) sounds by exploring patterns of interference when different modulation types originated from different loci as may occur in a multisource acoustic field.
Method: Interaural delay thresholds were measured from 5 normal-hearing adults for an AM sound in the presence of interfering FM and vice versa as a function of interferer modulation rate. In addition, the effects of near versus remote interferer rates, and fixed versus randomized interferer interaural delay, were investigated.
Results: AM interfered with lateralization of FM at all modulation rates. However, the FM interfered with AM lateralization only when the FM rate was higher than the AM rate. This rate asymmetry was surprising given the prevalence of low-frequency dominance in lateralization, but was predicted by a cross-correlation model of binaural interaction. Effects were similar for fixed and randomized interferer interaural delays.
Conclusions: The results suggest that in multisource environments, sources containing different modulation types significantly interfere with localization in complex ways that reveal interactions between modulation type and rate. These findings contribute to the understanding of auditory object formation and localization.

KEY WORDS: sound localization, modulation, AM, FM, interference

Amplitude-modulated (AM) and *frequency-modulated* (FM) sounds are the building blocks of nearly all natural and complex sounds. Important examples include communication signals from speech to vocalizations in diverse species from nonhuman primates to marine mammals, birds, and even insects (Bailey, Greenfield, & Shelly, 1993; Brillet & Paillette, 1991; Coscia, Phillips, & Fentress, 1991; Dankiewicz, Helweg, Moore, & Zafran, 2002; Dear, Simmons, & Fritz, 1993; Fant, 1970; Huber & Thorson, 1985; Klump & Langemann, 1991; Pickett, 1980; Robisson, Aubin, & Bremond, 1993; Ryan & Wilczynskin, 1988; Saberi & Perrott, 1999; Sabourin, Gottlieb, & Pollack, 2008; Simmons, 1979). Interaural delay is one of the major cues to sound localization along the azimuthal plane and has been used extensively in the investigation of binaural spatial processing and interference effects in localization. In this study, we investigated the ability of human subjects to detect spatial cues (interaural delays) in mixed-modulated (MM) waveforms (i.e., sounds that contain concurrent AM and FM cues) and the extent to which spatial cues in one type of modulation interfere with coding of conflicting spatial cues in the other type of modulation.

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The rationale for exploring spatial interference across modulation types is partly derived from the idea that an FM signal is converted into AM as its instantaneous frequency sweeps through a cochlear filter's passband (Blauert, 1981; Henning, 1980; Hsieh & Saberi, 2009; Saberi, 1998; Saberi & Hafter, 1995). The induced AMs have rates and phases that are complex and dependent on a number of factors such as a filter's resonant frequency relative to that of the FM carrier. For a periodic FM, the system must integrate different AM rates and phases at the outputs of filters that fall within the FM's peak frequency excursion. Filters near the FM carrier frequency will output an AM rate twice that of more remote filters,[1] and the periodic AM envelopes at the outputs of filters positioned above and below the FM carrier will be antiphasic (Saberi, 1998). Given these complexities, it is a priori difficult to determine the magnitude or patterns of interference across modulation types without empirical measurement.

In a multisource acoustic environment, concurrently active sounds originating from different locations may interfere with detection, localization, and identification of a target sound. Prior studies of binaural interference have extensively investigated the effects of frequency differences on lateralization of concurrently active sources (Heller & Trahiotis, 1995, 1996; McFadden & Pasanen, 1976; Perrott, 1984; Saberi, Tirtabudi, Petrosyan, Perrott, & Strybel, 2002). Heller and Trahiotis (1995), for example, demonstrated that an AM stimulus can interfere with detection of interaural delays in another AM sound even when their carrier frequencies are several critical bands apart. In that and other similar studies (Best, Gallun, Carlile, & Shinn-Cunningham, 2007; Heller & Trahiotis, 1996), waveforms of a single modulation type (AM) with different carrier frequencies were used. In the present study, we used waveforms of different modulation types (AM/FM) but the same carrier frequency to investigate binaural interference as a function of modulation type and rate. In baseline control conditions, we also examined the ability to detect interaural delays in the absence of interference separately for AM, FM, and MM sounds whose FM and AM components had identical coherent interaural delays. Based on the idea that FM is converted to AM, we predicted substantial interference with detection of interaural delays across modulation types. In addition, based on irregularities in the induced AM's rate and phase across peripheral auditory filters, we predicted dissimilar interference patterns depending on which modulation type serves as the interferer as well as interactions between modulation type and rate.

General Method

Stimuli

Stimuli were generated using MATLAB software (The MathWorks) on a Dell PC (Dimension 8400) and presented at a rate of 44.1 kHz through 16-bit digital-to-analog converters (Creative Sound Blaster Audigy 2ZS) and through Sennheiser headphones (HD 433) in a double-walled steel acoustically isolated chamber (Industrial Acoustics Company). The AM, FM, and MM stimuli were generated from Equations 1 to 3, respectively:

$$X_{AM}(t) = \sin[2\pi f_c(t + ITD)][1 + m\sin(2\pi f_{AM}(t + ITD)] \quad [1]$$

$$X_{FM}(t) = \sin[2\pi f_c(t + ITD)] + \beta\sin[2\pi f_{FM}(t + ITD)] \quad [2]$$

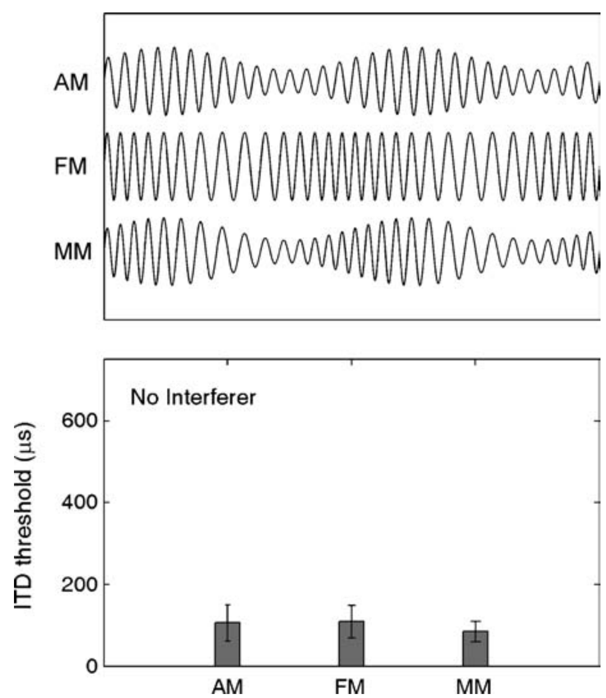
$$X_{MM}(t) = \{1 + m\sin[2\pi f_{AM}(t + ITD_1)]\}\sin[2\pi f_c(t + ITD_2)] + \beta\sin[2\pi f_{FM}(t + ITD_2)], \quad [3]$$

where f_{AM}, f_{FM}, and f_c represent the AM, FM, and carrier frequencies, respectively, in hertz; ITD is the interaural time difference; m is the amplitude modulation depth; and β is the frequency modulation depth (see Figure 1, top panel). The value of β was set to 1, and the value of m was set to 0.5 to ensure that the MM waveform maintained both AM and FM cues throughout the entire stimulus duration. Prior monaural studies of MM sounds have also typically selected values of m less than 1 (Moore & Sek, 1992, 1994). For the MM waveform, amplitude and frequency modulation rates (f_{AM} and f_{FM}) were equal when there was no interfering signal and were usually, but not always, different when one modulation type was selected as the interferer. Similarly, their respective interaural delays (ITD_1 and ITD_2) were different in the "interference" conditions.[2] We selected a high carrier frequency of 3 kHz in all conditions to avoid carrier interaural phase effects, which are dominant at frequencies below 1.5 kHz (Mills, 1960, 1972; Rayleigh,

[1] Filters near the FM carrier will output an AM that has a rate twice that of the FM as it sweeps through both the up and down slopes of the filter during the positive and again during the negative phase of the FM, whereas for more remote filters, the FM will sweep only through either the filter's up slope (lower frequency slope for filters with center frequencies [CFs] above the FM carrier) or the down slope (higher frequency slope for filters positioned below the FM carrier), hence generating an AM rate equal to that of the FM. Furthermore, the transition between these two extremes is graded, with the two AM peaks gradually merging into one as the distance between the FM carrier and filter CF is increased. This complex pattern also depends on the FM rate. For very rapid sweeps, the system will not track changes in instantaneous frequency. The AM is induced by filtering out sidebands of the long-term Fourier spectrum of the FM signal consisting of symmetric harmonics flanking the carrier frequency, with the lower odd harmonics inverted in phase relative to the carrier phase.

[2] In generating the dichotic stimuli from Equations 1 through 3, ITD was set to zero in one channel and to the desired interaural delay in the other channel.

Figure 1. The top panel shows time-domain representations of amplitude-modulated (AM), frequency-modulated (FM), and mixed-modulated (MM) waveforms. The MM waveform contains simultaneous AM and FM components. The bottom panel shows averaged interaural time difference (ITD) thresholds for the three types of waveforms in the absence of interference. The ITDs in both the AM and FM components of the MM waveform were equal ($ITD_1 = ITD_2$ in Equation 3). The waveforms had a carrier frequency of 3 kHz that was modulated at 200 Hz. Data are averaged from five subjects. Error bars indicate 1 standard error of the mean (*SEM*).



1907; Yost & Hafter, 1987). The signal to be detected was the change in interaural delay across the two intervals of a trial. We selected a modulation frequency of 200 Hz for the waveform containing the signal because this modulation frequency has been shown to produce low ITD discrimination thresholds for both AM and FM sounds (Saberi, 1998). Because previous work on binaural interference at high frequencies has suggested that modulation phase does not affect binaural interference (Heller & Trahiotis, 1995), we set the modulation phases to zero. Stimuli were 300 ms in duration, with 20-ms linear rise–decay envelopes. All waveforms had simultaneous onsets and offsets in the two channels to prevent use of interaural envelope cues at the beginning and end of the stimulus. Delays between left and right channels were checked for accuracy with a dual-channel digital storage oscilloscope (Tektronix, Model TDS210). Stimulus levels were calibrated to 70 dB SPL using a 6-cc coupler, 0.5-in. microphone (Brüel&Kjær, Model 4189), and a Precision Sound Analyzer (Brüel&Kjær, Model 2260).

Procedures

Five normal-hearing adults (3 male, 2 female), including 3 of the authors, served as subjects. Their ages ranged from 21 to 46 (*M* = 31.2). All were highly experienced in spatial hearing experiments, and each received 2 hr of practice on various conditions of the experiment before data collection began.

The experiment was run in a random-block design in which the modulation rate and type were held constant within a run. Each run consisted of 50 trials in a two-interval forced-choice (2IFC), two-down one-up adaptive design that tracks the subject's 70.7% correct response threshold (Levitt, 1971; Wetherill & Levitt, 1965). On the first interval of each trial, the dichotic waveform led to one randomly selected ear by a specific ITD; in the second interval, it led to the other ear by the same magnitude of ITD. The interstimulus interval was 250 ms. The subject's task was to identify the order of presentation of the stimuli (i.e., left-leading then right-leading, or right-leading then left-leading). Perceptually, this is equivalent to determining if the two intracranial auditory images in the two intervals of the trial were heard at left then right or at right then left. The subject then pressed either a left or a right key to respond (left key response meant that the subject perceived the sound orders as right to left). Visual feedback was provided after each trial. The initial value of the signal interaural delay on each run was 1,500 μs (i.e., 750 μs in each interval). Two successive correct responses led to a reduction of the total interaural delay by a stepsize of 0.2 log units up to the fourth reversal and 0.1 log units thereafter (Saberi, 1995b). An incorrect response led to an increase in ITD by the same stepsize. Threshold on each run was estimated as the average of the stimulus values at track reversal points. The first three or four reversals from each run were discarded, and threshold was estimated as the average of the remaining even number of reversals. Usually, four to eight reversals went into the calculation of each threshold. All procedures were approved by the University of California, Irvine's Institutional Review Board.

Lateralization Thresholds for AM, FM, and MM Waveforms in the Absence of Interference

The purpose of this part of the study was to measure baseline ITD thresholds for the different modulation types, to which we could compare thresholds from MM waveforms with conflicting ITD cues. It was a priori unclear whether the MM stimulus with coherent ITD cues in its FM and AM components within the same frequency region would produce thresholds different from those of AM or FM alone. Previous studies of spectrally remote co-modulated waveforms with common ITDs have shown improvements in ITD thresholds relative to thresholds obtained from independently modulated bands (Saberi, 1995a). All waveforms had a constant modulation rate of 200 Hz. The ITDs of both types of modulation in the MM waveform were the same (i.e., $ITD_1 = ITD_2$ in Equation 3) and varied adaptively as described in the *Procedures* section). Each subject completed four to five runs per each of three conditions in a random-block design.

Results

The bottom panel of Figure 1 shows averaged ITD thresholds from five subjects for the three types of modulation in the absence of interference. Thresholds across conditions averaged between 100 and 150 μs. No significant improvements in lateralization thresholds were observed when the two modulation types were co-modulated (MM) relative to AM and FM alone. This finding may be contrasted to the work mentioned previously (Saberi, 1995a), which has shown an enhancement of ITD thresholds when waveforms of the same modulation type across different spectral regions are co-modulated. A one-way repeated-measures analysis of variance (ANOVA) confirmed that there was no significant effect of modulation type, $F(2, 42) = 0.795$, *ns*.

Binaural Interference Across Modulation Type

The threshold for an MM waveform with coherent ITDs was the same as that measured for an FM or AM waveform alone. In this part of the study, we examined ITD thresholds for the AM component of an MM waveform when its FM component carried conflicting ITD cues and equivalently measured ITD thresholds for the FM component of an MM waveform when its AM component carried conflicting ITD cues. The stimulus was an MM waveform generated from Equation 3 with different modulation frequencies ($f_{AM} \neq f_{FM}$) and different interaural delays ($ITD_1 \neq ITD_2$) associated with each modulation type. In half the runs, the FM signal was the interferer; in the other half, the AM signal was the interferering modulation type. The ITD of the interfering modulation was set to zero, similar to designs used in other studies of binaural interference (Best et al., 2007; Heller & Trahiotis, 1995), whereas the ITD of the signal modulation was adaptively varied. The signal modulation frequency was always equal to 200 Hz, and the interfering modulation frequency was either 100 Hz, 200 Hz, or 300 Hz. We selected these rates for the interfering stimulus because they cover rates that produce relatively low to moderate lateralization thresholds for AM and FM sounds in isolation. Lateralization thresholds for rates below 100 Hz or exceeding 300 Hz precipitously increase (Henning, 1974, 1980; Nuetzel & Hafter, 1976, 1981; Saberi, 1998) and hence are likely to be nonoptimal as interfering stimuli. The task was the same as that described earlier except that subjects were informed that if they heard two perceptually distinct sounds, they should focus on that which appeared to change in spatial location across the two intervals of the trial and to use feedback to maximize performance. Each of the five subjects completed four to five runs per each of six conditions (3 rates × 2 modulation types) in a random-block design.

Results

Figure 2 shows individual-subject data from this experiment, and Figure 3 shows the mean results. The left column of Figure 2 and top panel of Figure 3 show the results for an AM signal and an FM interferer, and the right column of Figure 2 and bottom panel of Figure 3 show the results for an FM signal and an AM interferer. The abscissa in both figures represents the interferer modulation frequency. The dashed horizontal lines represent thresholds for the signal alone—that is, in the absence of the interfering waveform. Two trends are clearly evident. First, when the signal is AM, the FM does not interfere with lateralization for interferer rates at or below the signal modulation rate. However, the FM causes substantial interference when its rate is above that of the signal. This rate asymmetry in interference is surprising, given the well-known low-frequency dominance in lateralization and signal detection studies that have shown upward spread of masking (Divenyi, 1992; Egan & Hake, 1950; Hsieh & Saberi, 2009; Klein, Mills, & Adkins, 1990; Picard & Couturemetz, 1985). However, our finding is consistent with some binaural studies showing that a high-frequency interferer has a more pronounced effect than a low-frequency interferer on detecting the motion of a target sound in a multisource environment (Saberi et al., 2002). It is interesting to note that studies of monaural modulation masking (e.g., Ewert & Dau, 2000) have shown that for modulation rates near those used in the present study, maskers with modulation rates below the signal modulation rate have a substantially larger masking effect than those with rates above the signal, suggesting that the results observed here are not caused by asymmetries in filter slopes of higher rate modulation filters.

The second main finding from this part of the study, shown in the bottom panel of Figure 3 (and right panels of Figure 2), is that an AM interferer has a significant effect on lateralization of FM signals at all interferer rates tested. Note from the individual subject data shown in Figure 2 that although all subjects show a consistent asymmetric pattern of interference for an FM interferer and AM signal (left panels), the patterns are somewhat

Figure 2. The left panels show effects of a diotic FM interferer on lateralization of an AM signal for five subjects (rows), and the right panels show effects of a diotic AM interferer on lateralization of an FM signal for the same five subjects. Note that the ordinate range differs across subjects to facilitate visual inspection given the wide range of thresholds. The dashed lines represent ITD thresholds for each signal type in the absence of interference.

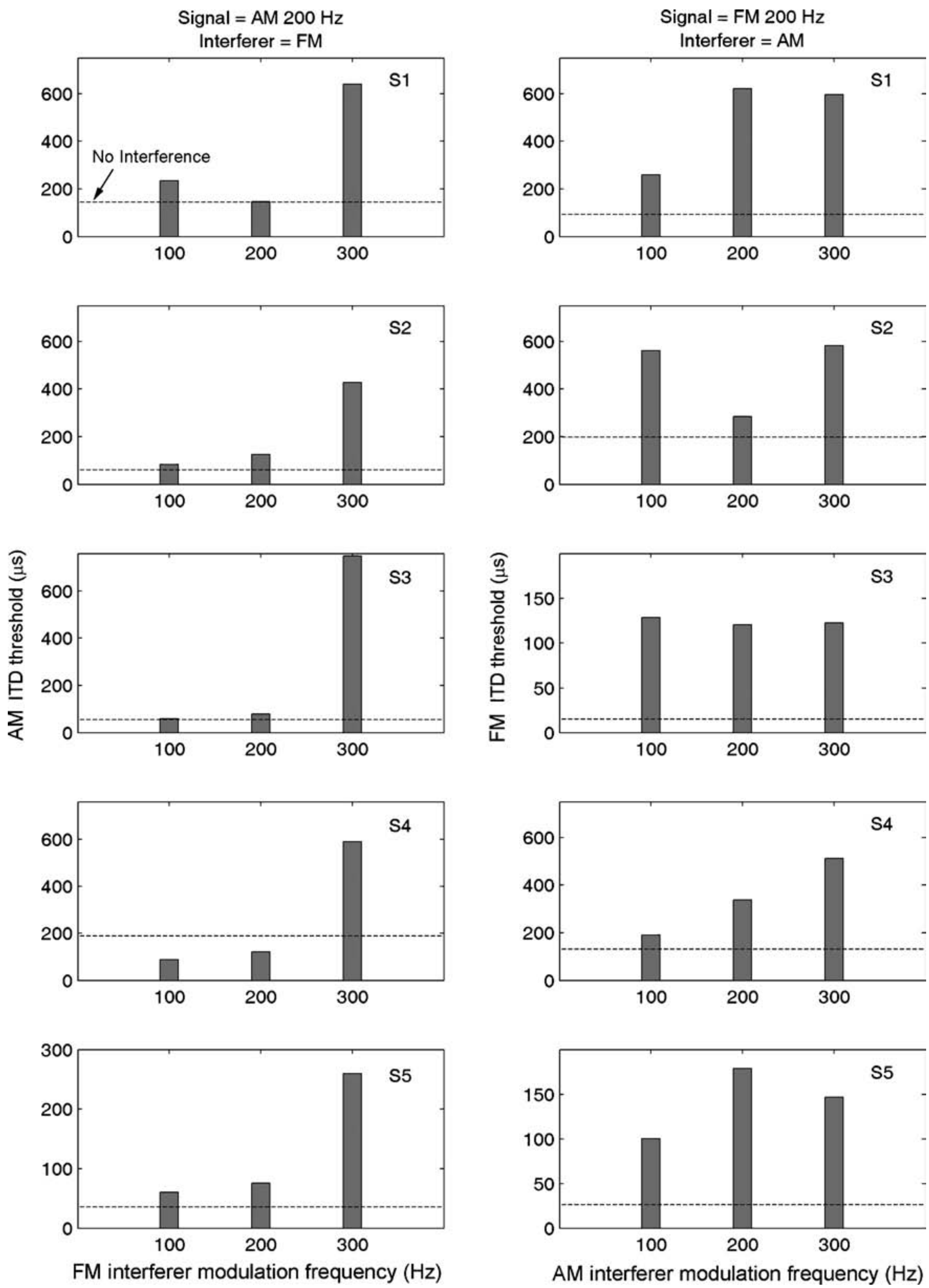
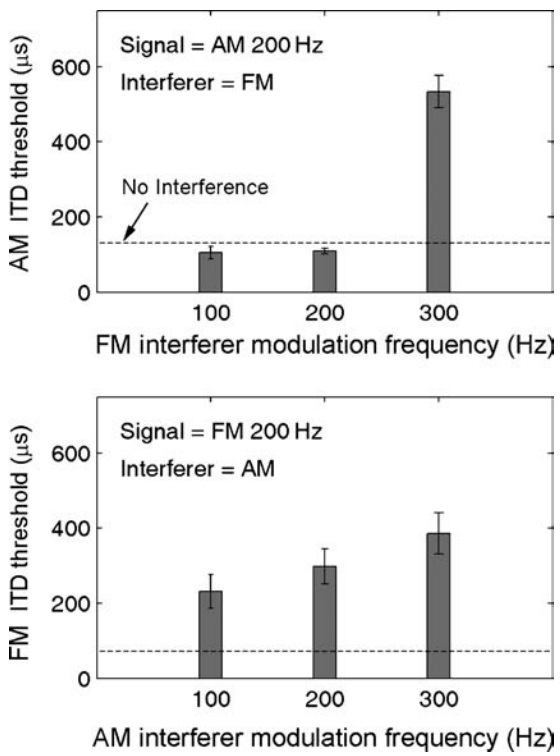


Figure 3. The top panel shows effects of a diotic FM interferer on lateralization of an AM signal, and the bottom panel shows effects of a diotic AM interferer on lateralization of an FM signal. The dashed lines represent ITD thresholds for each signal type in the absence of interference. Data are averaged from five subjects. Error bars indicate 1 *SEM*.



more variable across subjects for the FM signal and AM interferer (right panels). Nonetheless, even in this case, thresholds for all subjects across all conditions (i.e., all 15 bars) are higher than thresholds in the absence of the AM interferer (dashed lines). Large intersubject variability has also previously been reported in studies of binaural interference (Best et al., 2007; Heller & Trahiotis, 1995).

To determine whether the observed differences between modulation types (AM vs. FM interferer) as well as between interferer modulation frequencies were significant, we conducted several statistical analyses. A two-way (2 × 3) repeated measures ANOVA on the data of Figure 3 showed a significant effect of interferer modulation frequency, $F_{\mathrm{Freq}}(2, 42) = 59.82, p < .001$; no significant effect of interferer modulation type, $F_{\mathrm{AM/FM}}(1, 21) = 2.08$, *ns*; and a significant Interferer Modulation Frequency × Type interaction, $\mathrm{F}_{\mathrm{Freq \times AM/FM}}(2, 42) = 20.54$, $p = .001$. As this ANOVA demonstrates an overall significant difference between conditions, in order to specifically determine which conditions caused significant interference, we conducted several paired-sample post hoc t tests. Results showed that for an AM signal and FM interferer, only the 300-Hz interferer (see Figure 3, top panel, right bar) caused a significant increase in thresholds relative to the no-interference (dashed-line) condition, $t(21) = 10.16$, $p < .001$. Neither the 100-Hz nor the 300-Hz FM interferer caused thresholds to change significantly relative to the no-interference condition: $t(21) = 0.20$, *ns*, and $t(21) = 0.21$, *ns,* respectively. However, when the signal was FM, an AM interferer caused significant interference at all three interferer modulation rates of 100 Hz, $t(21) = 2.81$, $p < .05$; 200 Hz, $t(21) = 4.02$, $p < .005$; and 300 Hz, $t(21) = 5.17$, $p < .001$.

Effects of Small Rate Differences and ITD Perturbation

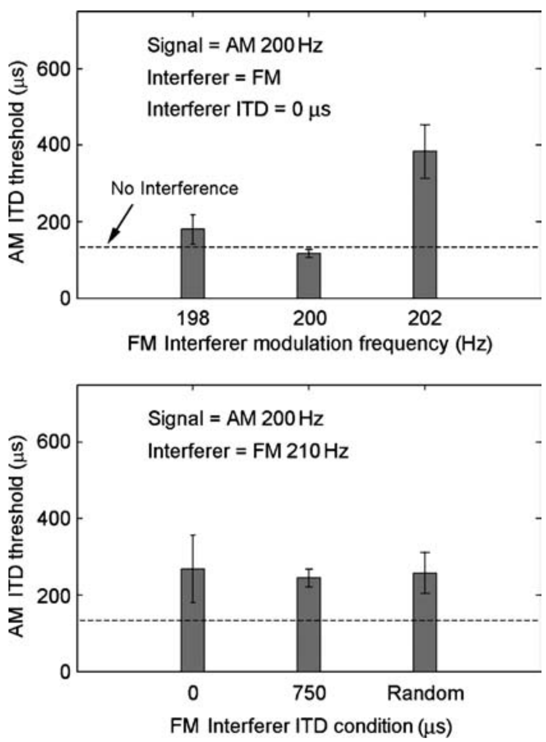
We conducted two additional complementary experiments using MM waveforms that examined very small modulation rate differences between the signal and interferer as well as the effects of perturbing the ITD of the interfering stimulus from trial to trial. We selected only the AM signal condition because of the substantially larger number of psychophysical (Henning, 1974; Nuetzel & Hafter, 1976), neurophysiological (Grothe & Park, 1998; Joris & Yin, 1992), and neuroimaging (Giraud et al., 2000; Wienbruch, Paul, Weisz, Elbert, & Roberts, 2006) studies that have focused on detection and lateralization of AM signals and also because we found the interesting asymmetric rate effects on lateralization of AM signals (see top panel of Figure 3). Three of the five subjects (S1, S2, S3) from the earlier parts of the study participated in the experiments described in the two sections that follow. Each subject completed three runs per condition.

Effects of Small Rate Differences

In the first part of the study, we measured lateralization thresholds for an AM signal in the presence of an FM interferer whose modulation rate was only 2 Hz away from that of the signal. In the previous section, the interferer modulation rate was either equal to or 100 Hz away from the signal modulation rate. When the interferer and signal modulation rates are distant, the percepts segregate into two streams in spite of the common carrier frequency. When the rates are near each other (but not equal), a fundamentally different percept is induced that may be described as perceptual beats at the rate difference (2 Hz). All procedures were the same as those described in the General Method section except that the interferer was FM at rates of 198 Hz or 202 Hz, and the signal was AM at 200 Hz.

The top panel of Figure 4 shows the results of this experiment. For comparison, the data for a 200-Hz FM

Figure 4. The top panel shows effects of cross-modulation interference as a function of small rate differences. The bottom panel shows effects of interferer ITD condition on lateralization thresholds: (1) diotic interferer, (2) fixed interferer ITD of 750 μs, (3) random selection of ITD interferer on each interval of the two-interval task from a uniform distribution (–750 μs to 750 μs). Data are averaged from three subjects. Error bars indicate 1 *SEM*.



interferer were replotted from the top panel of Figure 3. The form of interference was nearly identical to that observed for larger rate differences in that the lower rate interferer (198 Hz) had a much smaller effect on lateralization of the AM signal than the higher rate interferer (202 Hz), which significantly degraded lateralization performance. A one-way ANOVA on these data showed a significant effect of interferer rate, $F(2, 22) = 12.10$, $p < .001$. Threshold for the 198-Hz condition was not significantly larger than that for the no-interference condition (dashed line), $t(11) = 1.62$, *ns*, whereas the threshold for the 202-Hz interferer was significantly larger than that for the no-interference condition, $t(11) = 4.37$, $p = .001$.

Effects of Interferer ITD Perturbation

In the main experiment, the interferer ITD was held constant at zero. We made this choice to be consistent with other studies of binaural interference (e.g., Heller & Trahiotis, 1996). However, it might be expected that having a fixed ITD for the interferer may produce a different magnitude of interference compared with an interferer whose ITD is either randomly selected on every presentation or is fixed at a relatively large nonzero extreme. To test this possibility, we examined binaural interference with lateralization of AM signals by an FM interferer whose ITD was either randomly selected on each presentation (i.e., different in the two intervals of the 2IFC) or fixed at 750 μs. The latter design is similar to one used in a binaural interference study by Buell and Hafter (1990), who used fixed-ITD interferers to examine lateralization of low-frequency complex tones. They reported that when the target and interferers comprised harmonic components, substantially larger interference effects were observed compared with when inharmonic complex tones were used. In the random-ITD condition, the interaural delay was picked from a uniform distribution with a range of 1,500 μs (750 μs leading to the left ear to 750 μs leading to the right ear). Because we had examined both large and small rate differences (2 Hz and 100 Hz), to further add to the set of interferer rates examined, we selected an interferer rate that was slightly different (i.e., 210 Hz) from those used earlier. We believe that this choice should not affect interpretation of findings from this part of the study, as our main interest here was to contrast the effects of zero, fixed (nonzero), and nonstationary ITDs on binaural interference.

The bottom panel of Figure 4 shows the results of this experiment. A one-way ANOVA on the data of the bottom panel of Figure 4 showed no significant difference between conditions, $F(2, 16) = 1.05$, *ns*. Note that the magnitude of interference was independent of whether the interferer ITD was 0, 750 μs, or randomized on each presentation. Note also that the magnitude of interference for the 202-Hz FM interferer (see top panel of Figure 4) is actually larger than that for the 210-Hz FM interferer. This suggests that although FM sounds that have rates above an AM signal's rate cause interference, the form of this interference as a function of rate may be nonmonotonic, both for FM interferer rates above and possibly below the AM signal rate.

Discussion

The present findings suggest that in a complex multisource environment where concurrent sounds originate from different loci, the presence of one type of modulation may affect the ability to localize another source containing a different form of modulation. An unexpected finding with AM signals and FM interferers was that higher interferer modulation frequencies had a more pronounced effect than lower frequencies. This pattern was not observed when the signal was FM and the interferer was AM, where significant interference was observed even at the lowest interferer modulation frequency (i.e., 100 Hz). We also found that perturbing the interferer ITD across intervals of a trial produced approximately the same magnitude of interference as that associated with a fixed-ITD interferer. In addition, we found that whether the AM signal and FM interferer modulation frequency differences are small (2 Hz) or large (100 Hz), similar asymmetric threshold patterns are observed. The present findings on cross-modulation interference are novel and complementary to other studies of binaural interference, which have shown that localization of a modulated waveform is adversely affected by the presence of the same type of modulation at a different frequency band (Heller & Trahiotis, 1995, 1996).

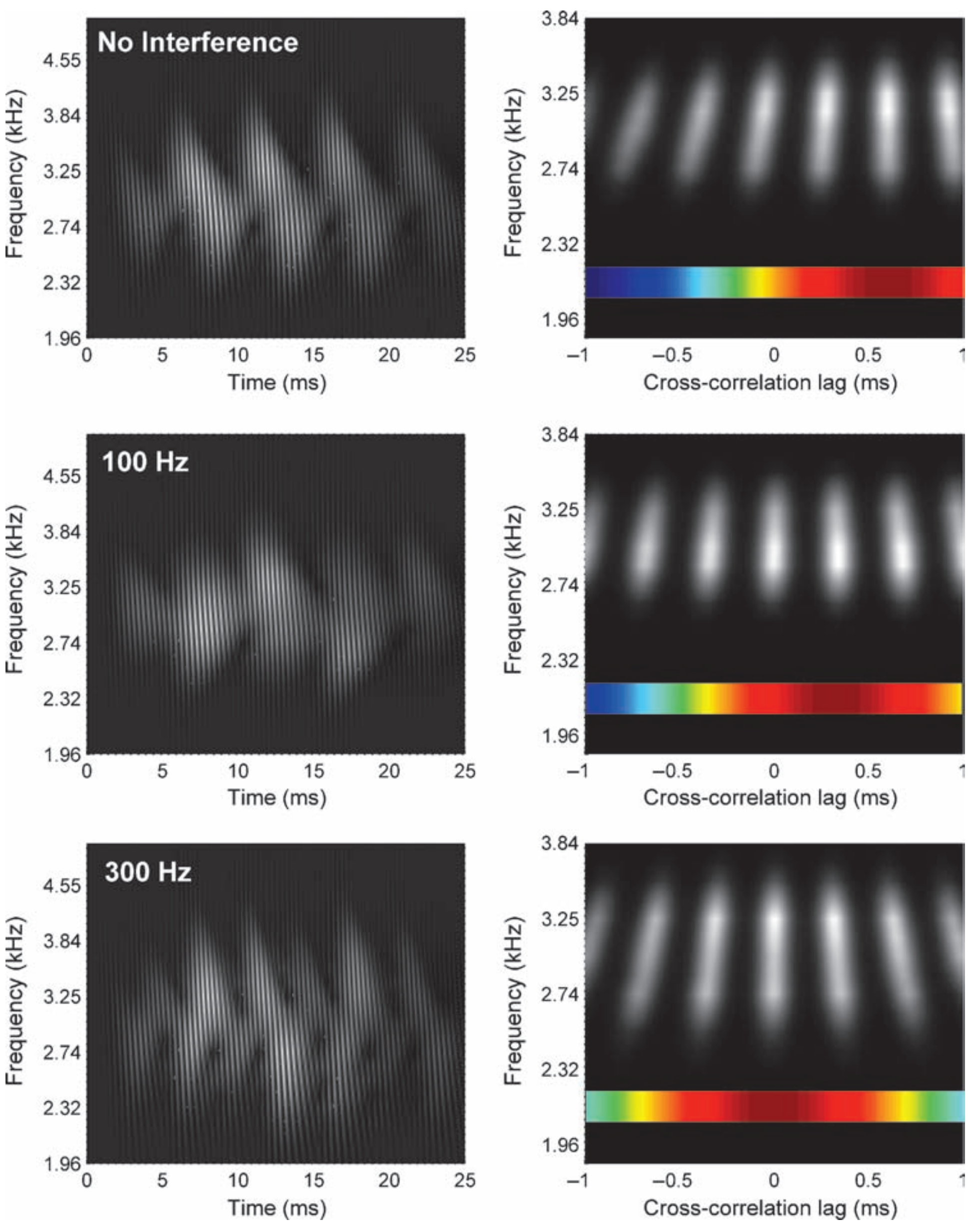
An important question to address here is the cause of the observed cross-modulation interference. As noted in the introduction, an FM-to-AM mechanism may provide part of the explanation for the interference effects. However, it is not intuitively clear why and how such a mechanism results in the observed patterns of binaural interference. The most notable of these patterns is the asymmetric effects of FM interferer rate on lateralization of AM sounds. Our goal here is not to conduct an extensive analysis of all conditions but, rather, to account for the unexpected finding that higher-rate FM interferers impact lateralization of AM signals more severely than do lower-rate interferers.

For this analysis, we processed the stimuli used in our experiment through a cross-correlation model of binaural interaction. This type of computational model, which originated in the theoretical work of Jeffress (1948) and later found neurophysiological support (Carr & Konishi, 1988, 1990; Yin & Chan, 1990), represents an interaural delay as a spatially distributed physiological place map. Peaks of activity along this tonotopically organized frequency-by-delay map correspond to estimated perceived locations in space. Our implementation of the model included a pre-processing stage (see left panels of Figure 5) consisting of a GammaTone filterbank with 40 filters whose center frequencies (CFs) were logarithmically spaced from 1 kHz to 5 kHz (Holdsworth et al., 1988) and an inner hair-cell model (Meddis, Hewitt, & Shackleton, 1990; Slaney, 1998), followed by cross-correlation of the outputs of corresponding left and right channels with matched-CF filters. The output of this model is shown in the right panels of Figure 5. Three types of mixed-modulated waveforms were processed. First, both the FM and AM components were modulated at 200 Hz, and both had consistent ITDs equal to +600 μs (i.e., no interference). The second and third types of waveforms corresponded to interference conditions—specifically, to the data shown in the top panel of Figure 3, in which the AM signal had an ITD of +600 μs and the FM interferer had an ITD of zero (positive ITDs in this model correspond to a dichotic waveform leading to the right ear). The signal AM was always modulated at 200 Hz, whereas the FM interferer was modulated at either 100 Hz or 300 Hz.

The predicted perceived lateral position is obtained by integrating the cross-correlation surface activity across frequency channels and determining the cross-correlation lag associated with the peak of this integrated activity (Hsieh & Saberi, 2009; Saberi, 1998; Saberi & Petrosyan, 2005; Stern et al., 1988). Because carrier interaural delay has a negligible effect on lateralization at high frequencies (Neutzel & Hafter, 1981), we used the peak of the envelope of integrated activity as the predictor of perceived position. This envelope was extracted using the Hilbert Transform and plotted as the intensity strip in the right panels of Figure 5. The dark red region corresponds to the lag associated with the envelope's peak. Note that the 100-Hz FM interferer affects the predicted perceived lateral position substantially less than the 300-Hz interferer. In the presence of limiting internal noise, the smallest lateral position estimate (associated with the 300-Hz condition) will lead to the largest predicted ITD threshold, consistent with the data observed in Figure 3. The 100-Hz interferer does predict a reduction in extent of laterality relative to no interference. This is not observed in the data of Figure 3 but is seen in the small-rate-difference data of Figure 4 (top panel). We can obtain predictions closer to those of Figure 3 but at the cost of an additional free parameter, which we thought was unnecessary. The critical observation is that a simple cross-correlation model with zero free parameters can predict the asymmetric interferer-rate effects on lateralization of AM signals.

The differences, both methodological and perceptual, between the present and previous studies of binaural interference may provide some insight into the neural processes underlying the observed interference within and across modulation types. There are two primary methodological differences between the present study and previous studies of binaural interference that have employed modulated tones. First, as noted earlier, prior studies examined interference of an AM tone on another spectrally remote AM tone. Second, these studies always used equal interferer and target modulation rates. For example, Heller and Trahiotis (1995) examined ITD discrimination thresholds for a high-frequency sinusoidally amplitude modulated (SAM) tone (2-kHz or 4-kHz carrier modulated at 250 Hz) in the presence of an interfering SAM tone at a different carrier but the same modulation frequency. They found that the largest interference was caused by a low-carrier-frequency (500 Hz) SAM tone. In a second study, Heller and Trahiotis (1996)

Figure 5. Lateral position predictions for MM waveforms processed through a cross-correlation model of binaural interaction. Stimuli were initially processed through a front-end filterbank and hair-cell model (left panels) followed by cross-correlation of the outputs of CF filters (right panels). Dark red (intensity bar) represents the peak of the envelope of integrated cross-correlation activity across frequency channels. This peak is associated with the extent of predicted laterality (see text). Positive and negative lags represent lateral positions on the right and left sides, respectively, of the interaural axis. The AM rate was 200 Hz with an ITD of +600 μs in all cases. Top panels: FM rate = 200 Hz, ITD = 600 μs (i.e., no interference). Middle panels: FM interferer = 100 Hz, ITD = 0 μs. Bottom panels: FM interferer = 300 Hz, ITD = 0 μs. CF = matched-center frequency.



reported that the perceived lateral position of a high-frequency SAM tone is also affected by presence of a low-frequency interfering SAM tone; the interferer effectively "pulled" the target toward itself. The fact that the target and interferer in these studies were spectrally remote suggests that this type of interference likely occurs at higher levels in the binaural pathway past the initial stages of binaural interaction in peripheral nuclei (e.g., the superior olivary complex). This idea is consistent with the findings of Best and colleagues (2007), who showed reduced binaural interference when a spectrally remote SAM-tone interferer was preceded and followed by a sequence of identical SAM tones that "captured" the interferer, presumably due to perceptual grouping.

The neural origins of interference effects reported by these studies may be at least partially different than those associated with ours. In our study, the target and interferers had the same carrier frequencies, and, as suggested by the cross-correlation analysis, the patterns of interference may have been partly caused by peripheral auditory processes. This does not mean that additional higher-level streaming or grouping mechanisms were not involved. In fact, as noted earlier, when the target and interferer had substantially different modulation rates, observers at times reported two perceptual streams, suggesting that interference across modulation types also may have been affected by central mechanisms involved in auditory object formation. What would one then expect to observe if the FM and AM waveforms were positioned in spectrally remote regions? We would still expect cross-modulation binaural interference but of a smaller magnitude compared with the effects reported in the present study or those reported in previous studies using spectrally remote AM targets and interferers. This is because—assuming that the FM waveform is transformed into AM information during bandpass filtering—it is likely that some level of interference would be observed consistent with prior studies using spectrally remote AM sounds. However, because the rates and phases of the induced AMs would be inconsistent across filters,[3] it is less likely that the magnitude of this type of interference would be as large as that reported in earlier studies.

In conclusion, our findings contribute to the understanding of object formation and localization in multi-source environments, and together with those from studies of stream segregation, spatial masking, and monaural and multimodal localization (Bregman, 1994; Brungart, Simpson, Ericson, & Scott, 2001; Freyman, Balakrishnan, & Helfer, 2004; Kidd, Richards, Mason, Gallun, & Huang, 2008; Musicant & Butler, 1985; Saberi, Dostal, Sadralodabai, Bull, & Perrott, 1991; Strybel & Vatakis, 2004) provide a more comprehensive picture of signal detection and identification in complex acoustic fields.

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[3]See Footnote 1.

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