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Lateralization on the Basis of Interaural Envelope Delays: The Effect of Component Starting Phase

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by

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VITA

The author, Andrew Joseph Niemiec, is the son of Andrew Niemiec and Stanislawa Katazyna (Kuczak) Niemiec. He was born March 17, 1962, in Chicago, Illinois.

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TABLE OF CONTENTS

Page

LIST OF FIGURES

INTRODUCTION

The duplex theory of sound localization asserts that interaural intensity differences (IIDs) are used to localize high-frequency sounds while interaural time or phase differences (ITDs) are used to localize low-frequency sounds (Rayleigh, 1907). The duplex theory was presented to account for data obtained with pure tone stimuli and does not account for localization of complex stimuli. For spectrally complex stimuli, ITDs can serve as powerful cues for sound localization at high frequencies given that some aspect of the temporal waveform repeats itself at a rate low enough to allow entrainment by the auditory neurons (McFadden and Moffitt, 1977).

Sensitivity to ITDs at high frequencies has been demonstrated with amplitude-modulated, high-frequency carriers (Henning, 1974; Nuetzel and Hafter, 1976; McFadden and Moffitt, 1977; Henning, 1980; Henning and Ashton, 1981; Nuetzel and Hafter, 1981; and Bernstein and Trahiotis, 1985). Work with amplitude-modulated, high-frequency carriers has established that sensitivity decreases as modulation depth is reduced (Henning, 1974; 1980). This conclusion was drawn from studies where subjects were presented with two observation intervals in each trial. In each of these observation intervals, the stimulus to one ear was delayed relative to the other ear. The subject was to identify the interval in which the stimulus was delayed to the right ear, that is, the interval when the stimulus sounded furthest to the left. The probability of the delayed stimulus being presented to the right ear in the first observation interval was 0.5 on each trial.

For amplitude-modulated, high-frequency carriers, there can be three types of ITD: carrier delays, waveform delays, and modulation or envelope delays. For a carrier delay, all components of an amplitude-modulated signal are delayed to one ear relative to the other by the same amount. For a waveform delay, both the fine structure and the envelope of the signal are delayed to one ear relative to the other. For an envelope or modulation delay, only the envelope of the signal is delayed to one of the ears relative to the other. Henning (1974) and Nuetzel and Hafter (1976) have shown that there is little difference in lateralization performance for waveform and envelope delays of high-frequency carriers. This indicates that the envelope, not the fine structure, is important for localizing high-frequency complex stimuli on the basis of ITDs. Henning (1980) and Henning and Ashton (1981) found that at carrier frequencies below 1600 Hz observers are sensitive to carrier but not envelope delays. This indicates that interaural delays between the fine structure at the two ears dominate localization. Above 1600 Hz there is no effect when carrier and modulator delays are put in opposition. Bernstein and Trahiotis (1985), however, found that although lateralization at low frequencies is dominated by carrier delays, it is also influenced by envelope delays.

Blauert and Cobben (1978) propose one possible model for the extraction of interaural delays at high frequencies. In this model, the signal at each ear is band-pass filtered to reflect peripheral filtering by the auditory system, half-wave rectified to reflect the fact that only rarefaction produces eighth-nerve fiber discharges, and low-pass filtered to reflect the loss in synchrony above 1600 Hz. Finally, a running cross-correlation is carried out on the outputs of the two ears. The cross-correlation between two signals is a measure of the similarity between the signals. Because it is also a function of the time delay between the two signals, the running cross-correlation can derive the interaural delay between the two channels. The model assumes that binaural processing of the extracted envelopes occurs within, not across, channels. That is, exactly the same type of signal processing is assumed to be carried out for auditory channels distributed across the frequency domain.

Others have proposed similar envelope extraction mechanisms (Duifhuis, 1973; Lindemann, 1986; Shear, 1987). These envelope extraction mechanisms all involve some type of non-linearity followed by low-pass filtering. Examples of possible non-linearities include exponential rectification and vth-law half-wave rectification (Shear, 1987). The advantage of using a half-wave rectifier or other even power-law rectifier in the Blauert and Cobben model is that the envelope extraction mechanism yields positive going waveforms which more accurately represent the physiological data.

Although any non-linearity followed by low-pass filtering constitutes a classic envelope detector and is widely accepted as the basis by which envelopes are extracted for binaural processing (Henning, 1974; McFadden and Pasanen, 1976; Nuetzel and Hafter, 1976; Blauert and Cobben, 1978; Henning, 1980; Nuetzel and Hafter, 1981), Henning has argued against this mechanism. Henning (1980) measured the ability of observers to use interaural delays in sinusoidally amplitude-modulated tones (SAM) and in quasi-frequency-modulated tones (QFM). QFM produces the same amplitude spectrum as SAM, but the starting phases of the sidebands are shifted 90° relative to the carrier. In contrast, AM sidebands have the same starting phase as the carrier. As a consequence, QFM waveforms have only small ripples in the temporal waveform which occur at twice the modulation frequency. These small ripples in the envelope have a small peak to trough amplitude and therefore a minimal effective depth of modulation. Henning argues that a binaural system consisting of the elements described in the Blauert and Cobben (1978) model would have great difficulty lateralizing the QFM waveforms on the basis of envelope delay because the minimal effective depths of modulation would not allow for envelope extraction by the envelope detector. Henning's results showed that performance was worse with QFM than with SAM and Henning concluded that performance with QFM was not as poor as would have been expected on the basis of simple envelope detection, however, Henning did not give the basis for his conclusion. Henning (1980) further demonstrated that lateralization on the basis of envelope delays differed little for QFM and true FM, although FM has no amplitude modulation whatsoever. Based on these findings, Henning concluded that binaural models such as Blauert and Cobben's do not account for the lateralization of high-frequency, amplitude-modulated waveforms on the basis of interaural envelope delay.

Blauert (1981) argued that FM waveforms undergo FM to AM conversion in the peripheral auditory system. In communications engineering, it is well known that an FM signal can be converted to an AM signal by band-pass filtering. In the time domain, as the instantaneous frequency of an FM signal falls within the pass band of a filter, the output of that filter will be determined by the frequency response of the filter to that frequency. The output of the filter will be an amplitude envelope that resembles the FM waveform as long as the modulation frequency is slow relative to the ring time of the filter. In the frequency domain, an FM signal is defined by short term spectral changes. Filtering the FM signal allows the reintroduction of amplitude modulation from the short term spectral changes. Because the lateralization of envelope-delayed FM and QFM waveforms can be explained by FM to AM conversion, the Blauert and Cobben model may continue to serve as a powerful conceptual tool for understanding binaural processing of ITDs at high frequencies. The intent of Henning's (1980) lateralization experiments was to minimize amplitude fluctuations in the waveform in order to test the basic premise of the Blauert and Cobben model. As explained, however, the signals used did not allow a strong test of the model since the short-term spectral changes accompanying QFM and FM allow amplitude modulation to be reintroduced by the peripheral auditory system. The ability of observers to lateralize these waveforms when the envelopes are interaurally delayed is not evidence against the model, and the inferior performance obtained with QFM and FM as opposed to AM is accounted for by lower effective depths of modulation at the outputs of the auditory filters.

To test the model, some means of signal generation which yield minimal envelopes with minimal short-term frequency sweeps are required. One possible solution to this problem is to randomize the starting phases of each of the components. The general strategy would be to diminish the effective envelope, holding the amplitude spectrum and interaural characteristics of the stimuli constant, by varying the starting phases of the components. This approach was used in the present study. To the extent that phase-randomization results in diminished amplitude fluctuations, one would expect poorer lateralization performance with envelope-delayed random phase complexes than with complexes whose components start in fixed phase. If, as the model assumes, increasing effective modulation depth of the stimuli aids in lateralization, then stimuli with additional components should be easier to lateralize than stimuli without additional frequency components. Adding two additional frequency components to the stimulus increases both peak to peak amplitude and peak to trough amplitude of the stimulus thereby increasing the effective modulation depth of the stimulus. If, as the model also assumes, binaural processing of the extracted envelopes occurs within a channel, lateralization performance should be better when all of the components of a stimulus fall within a channel, i.e. when modulation frequencies are low.

The general finding was that randomizing the starting phases of the signal components had only a small effect on the observers' ability to extract and process interaural envelope delays from high-frequency signals at higher modulation frequencies. At lower modulation frequencies, thresholds were

METHODS

The stimuli for this experiment were 200 ms bursts of a harmonic complex. Stimuli were digitally generated at a rate of 20000 points per second on a Masscomp computer and were composed of either 3 or 5 equal-amplitude sinusoids added together. The digital stimulus waveforms were turned on and off with 20 ms linear rise-fall times and were passed through Krohn-Hite 3343R low-pass filters set to 9000 Hz for anti-aliasing. F_C, the carrier frequency of the stimulus, was always 4000 Hz while the other components of the stimulus varied as a function of the modulation frequency, F_M. The term "modulation frequency" is used somewhat incorrectly since all components are equal in amplitude.

Modulation frequency ranged from 25 to 500 Hz. Thus a 3-component stimulus was composed of F_C and $F_C \pm F_M$ while a 5-component stimulus was composed of F_C, $F_C \pm F_M$, and $F_C \pm 2F_M$. The overall level of each stimulus waveform was 50 dB SPL. Stimuli were generated with fixed and random starting phase, yielding an experiment with four conditions: 3-components added in-phase, 3-components added with random starting phases, 5-components added in-phase, and 5-components added with random starting phases. Data for these conditions were collected in a counterbalanced order.

For the random starting phase conditions, ten pairs of random starting phase stimuli were generated for each block of 50 trials. Starting phases were randomized between the two intervals of the task by randomly choosing from the pool of 20 random phase stimuli. This was done to ensure that any particular set of random starting phases did not dominate a set of trials, since by chance, a single set of starting phases might yield waveforms very similar to the in-phase waveforms. The starting phases were chosen randomly from a rectangular distribution that ranged from 0° to 360°. Stimulus presentation was under computer control with each stimulus having an equal chance at being chosen on a particular trial.

Four trained subjects with no history of hearing disorders participated in the standard two-interval forced choice lateralization experiment. Three of the four subjects had experience with lateralization experiments and required minimal additional training. The fourth subject was trained to lateralize low-frequency pure tone stimuli before actual data collection was begun. The training period lasted approximately four weeks.

Each trial of the experiment had two observation intervals separated by a 250 ms inter-stimulus interval. In one interval, the stimulus envelope was delayed to the right ear. In the other interval, the stimulus envelope was delayed to the left ear. On each trial the probability of the signal being delayed to a particular ear during the first interval was 0.5. There were 50 trials per block with each subject generally running for two consecutive blocks at a given delay.

Envelope delays were generated by advancing the lower sideband of the stimulus while delaying the upper sideband. The center frequency was not delayed. This procedure yielded a "delayed" waveform whose amplitude spectrum was identical to the amplitude spectrum of a "non-delayed" waveform, however, the phase spectrum of the "delayed" waveform was changed. The phase shift, $\Delta\varnothing(f)$, for a component at frequency f is given by the equation $\Delta\varnothing(f) = -2\pi\Delta_t f + 2\pi\Delta_t f_c$, where Δ_t is the envelope delay in seconds.

The subjects were seated in a sound-attenuating chamber and the signals were presented over TDH-49 headphones. The subjects' task was to indicate whether the intracranial images associated with the stimuli moved from right-to-left or from left-to-right. Feedback was provided to the subjects on a trial-by-trial basis. Threshold delays, defined as the delays yielding d'=1.00, were determined by linear interpolation of the psychometric function based on a minimum of three different delays with at least 100 observations at each delay.

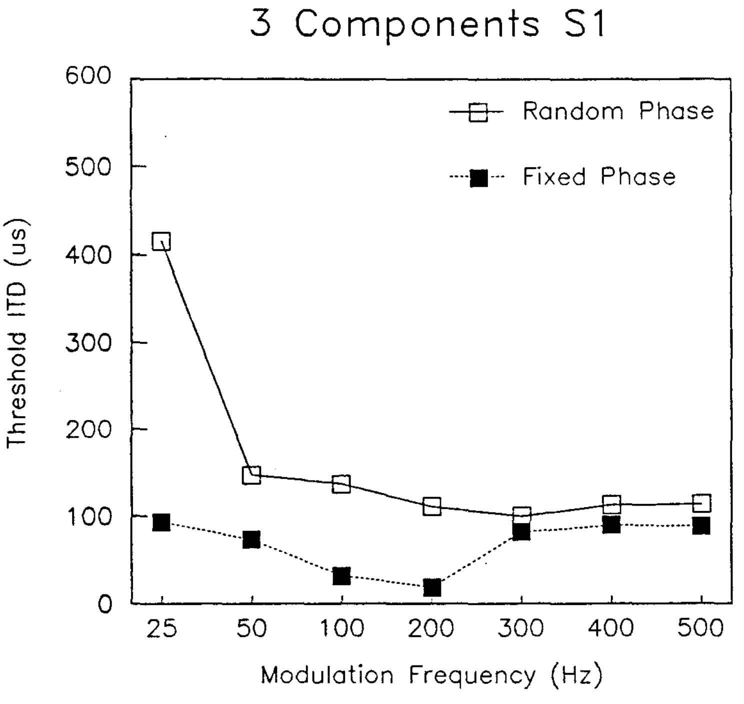
RESULTS

The results for each observer are shown in Figures 1-4. Threshold ITDs are plotted as a function of modulation frequency for each of the four subjects for 3- and 5-component complexes whose starting phases are either random (open symbols) or fixed at 0° (closed symbols). Subjects 1, 2, and 4 showed good overall acuity in the lateralization task. Although Subject 2 showed the best overall acuity in the lateralization task, his acuity declined at low modulation frequencies. Subject 3, the least experienced subject, showed the poorest overall acuity in the task.

For 3-component complexes at high modulation frequencies, randomizing the starting phases of the signal components had only a small effect on the observers' ability to extract and process interaural envelope delays. Subjects 1 and 2 show this small effect for modulation frequencies greater than or equal to 200 Hz, whereas Subjects 3 and 4 show the effect for modulation frequencies greater than 300 Hz. At lower modulation frequencies, however, randomizing the starting phases of the 3-component complexes significantly increased observer thresholds. The data from all four subjects show this effect. For 5-component complexes, phase-randomization had only a very small effect across all modulation frequencies for three of the subjects. The exception to this was Subject 3 who showed a large effect of phase-randomization for the 5-component stimuli. However, it should be noted that Subject 3 was the least experienced of the subjects and her data showed the greatest variability. If we compare the magnitude of the phase-randomization effect for the 3-component stimuli with the magnitude of the phase-randomization effect for the 5-component stimuli, Subject 3 shows a larger effect of phase-randomization for the 3-component stimuli than for the 5-component stimuli. This is in agreement with the general trend seen in the other subjects' data. Figure 5 shows typical 3- and 5-component complexes added in fixed and random starting phase. Although phase-randomization markedly affects the stimulus envelopes for both 3- and 5-component conditions, it significantly alters observers' lateralization performance only in the 3-component conditions with low modulation frequencies.

In most cases, observer performance with 5-component complexes was better than that obtained with 3-component complexes. Adding frequency components to the stimuli greatly decreased threshold ITDs at lower modulation frequencies (F_M < 200 Hz) when the additional components fell within the critical band at 4000 Hz. Thresholds at higher modulation frequencies decreased only slightly when additional sidebands were added.

Figure 1. Threshold ITDs plotted as a function of modulation frequency for 3- and 5-component complexes whose starting phases are either random (open symbols) or fixed at 0° (closed symbols). These are the data for Subject 1.


3 Components S1
Random Phase
Fixed Phase
Threshold ITD (us)
0
100
200
300
400
500
600
25
50
100
200
300
400
500
Modulation Frequency (Hz)

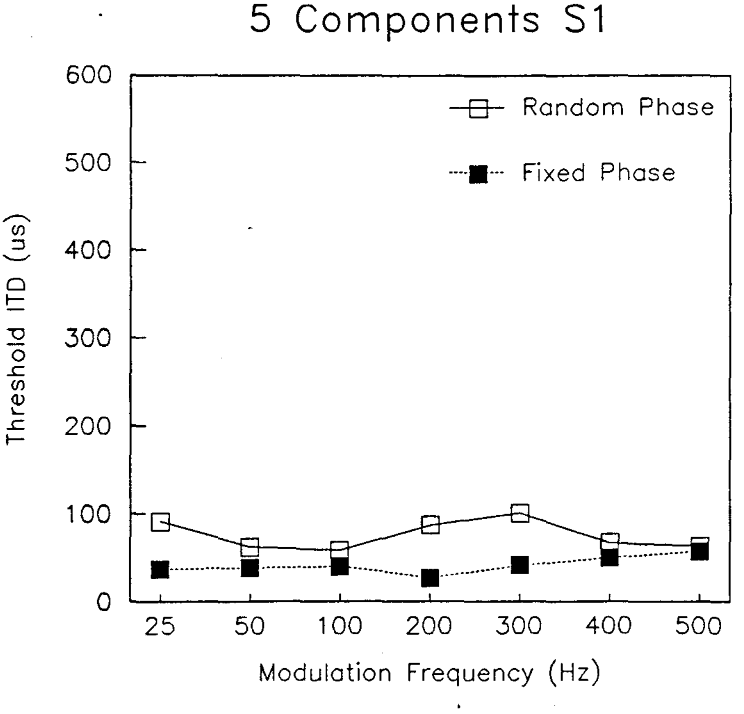
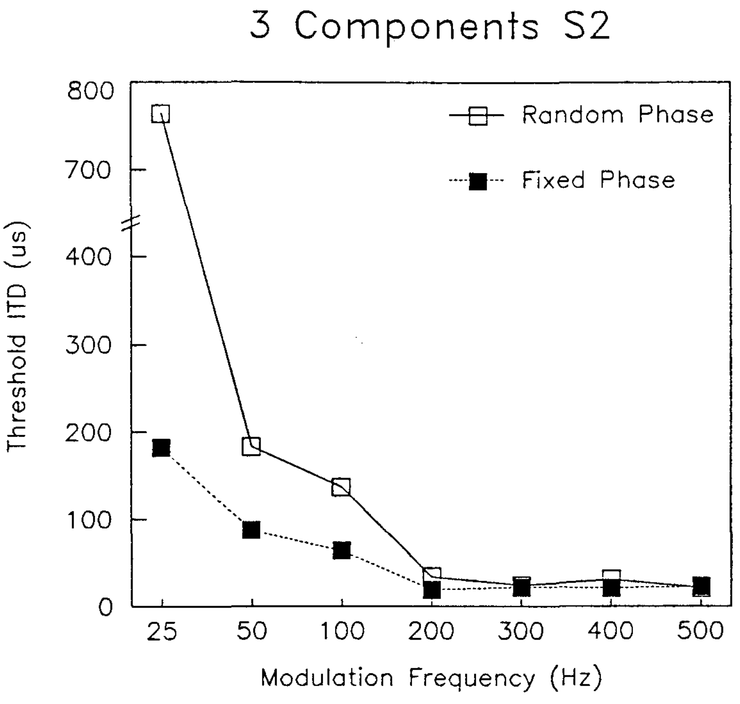

5 Components S1
Random Phase
Fixed Phase
Threshold ITD (us)
0
100
200
300
400
500
600
25
50
100
200
300
400
500
Modulation Frequency (Hz)

Figure 2. Threshold ITDs plotted as a function of modulation frequency for 3- and 5-component complexes whose starting phases are either random (open symbols) or fixed at 0° (closed symbols). These are the data for Subject 2.


3 Components S2
Random Phase
Fixed Phase
Threshold ITD (us)
800
700
400
300
200
100
0
25
50
100
200
300
400
500
Modulation Frequency (Hz)

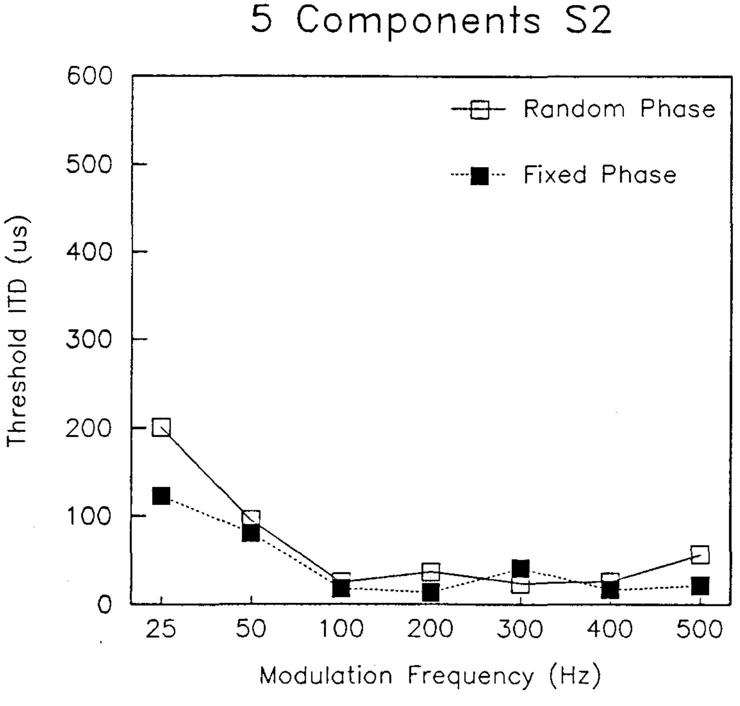
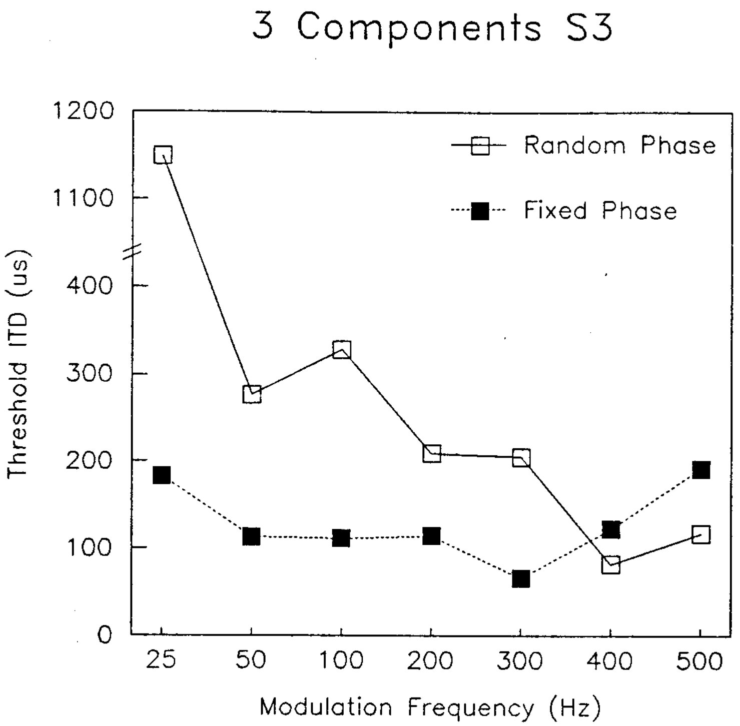

5 Components S2
Random Phase
Fixed Phase
Threshold ITD (us)
600
500
400
300
200
100
0
25
50
100
200
300
400
500
Modulation Frequency (Hz)

Figure 3. Threshold ITDs plotted as a function of modulation frequency for 3- and 5-component complexes whose starting phases are either random (open symbols) or fixed at 0° (closed symbols). These are the data for Subject 3.


3 Components S3
Threshold ITD (us)
1200
1100
400
300
200
100
0
25
50
100
200
300
400
500
Modulation Frequency (Hz)
Random Phase
Fixed Phase

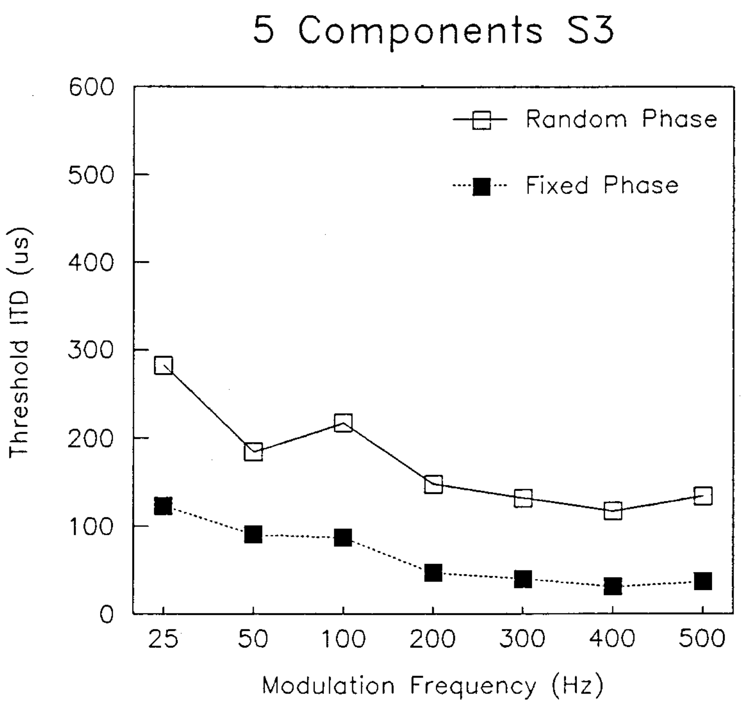
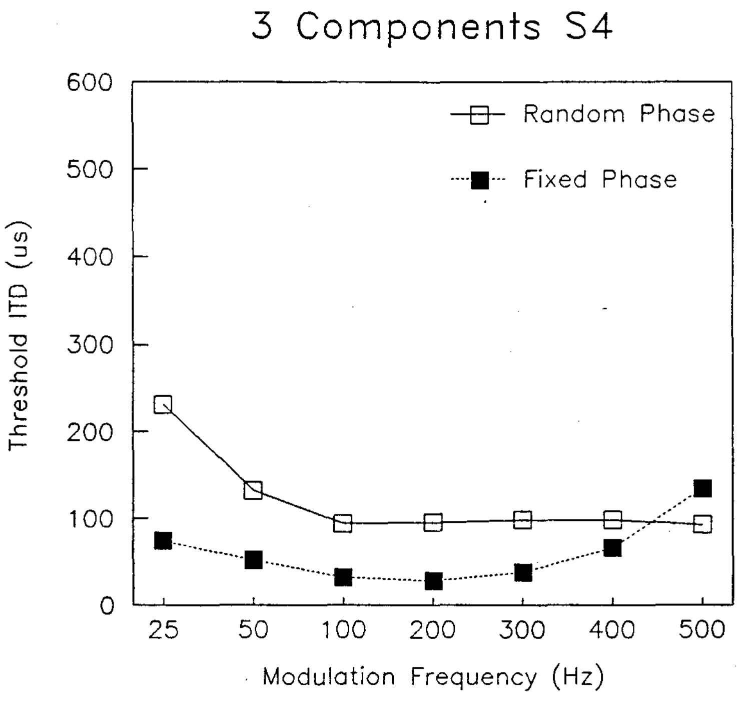

5 Components S3
Threshold ITD (us)
600
500
400
300
200
100
0
25
50
100
200
300
400
500
Modulation Frequency (Hz)
Random Phase
Fixed Phase

Figure 4. Threshold ITDs plotted as a function of modulation frequency for 3- and 5-component complexes whose starting phases are either random (open symbols) or fixed at 0° (closed symbols). These are the data for Subject 4.


3 Components S4
Random Phase
Fixed Phase
Threshold ITD (us)
600
500
400
300
200
100
0
25
50
100
200
300
400
500
Modulation Frequency (Hz)

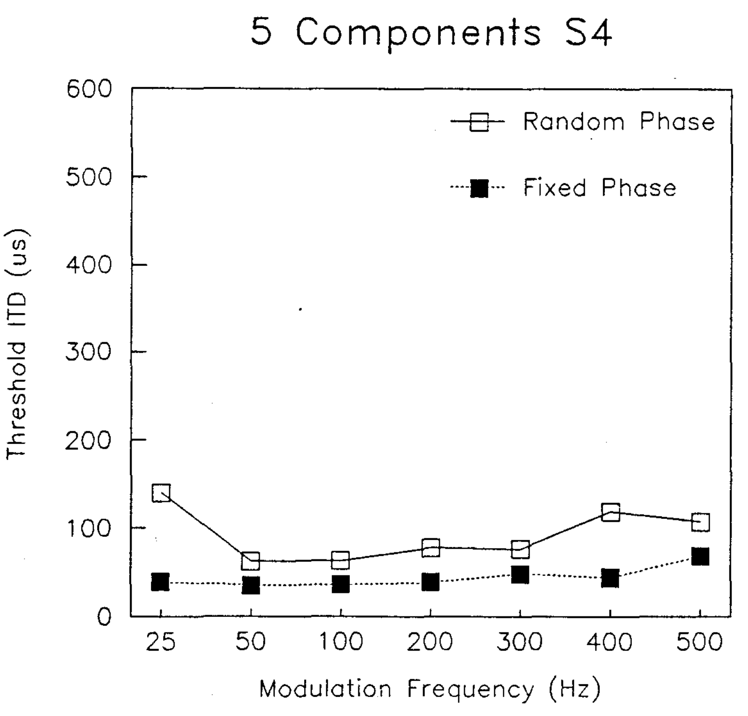
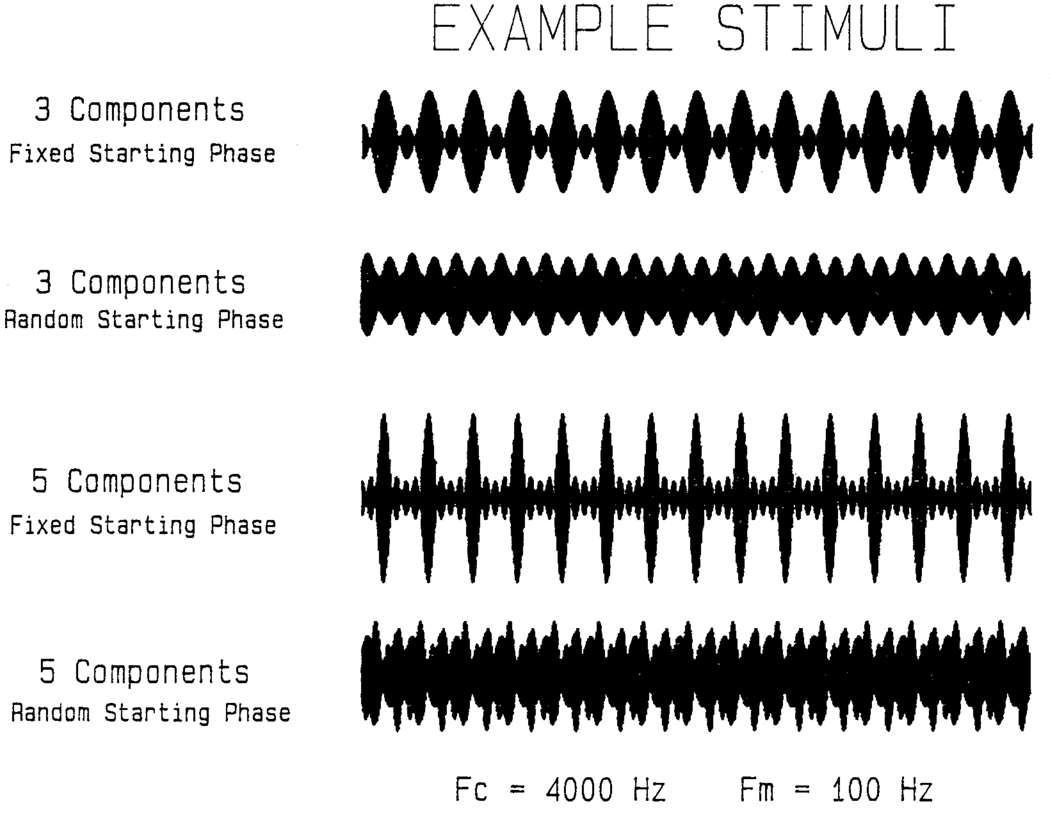

5 Components S4
Random Phase
Fixed Phase
Threshold ITD (us)
600
500
400
300
200
100
0
25
50
100
200
300
400
500
Modulation Frequency (Hz)

Figure 5. Typical 3- and 5-component complexes added in fixed and random starting phase for a carrier frequency of 4000 Hz and a modulation frequency of 100 Hz. Note that although phase-randomization markedly affects the stimulus envelope for both the 3- and 5-component conditions, it significantly alters observers' lateralization performance only in the 3-component conditions with low modulation frequencies.


EXAMPLE STIMULI
3 Components
Fixed Starting Phase
3 Components
Random Starting Phase
5 Components
Fixed Starting Phase
5 Components
Random Starting Phase
Fc = 4000 Hz
Fm = 100 Hz

DISCUSSION

As can be seen from Figures 1-4, threshold ITD decreases as modulation frequency increases. At first glance, these data seem to indicate that lateralization performance improves with increasing number of observations. That is, as modulation frequency increases, the subjects get more "looks" at the stimulus envelope and these additional looks provide additional information about the stimulus. However, as modulation frequency continues to increase, the number of looks and the rate at which the looks occur increases to the point where the looks can no longer be processed optimally, and threshold ITD again begins to rise.

To examine whether the results of this study could be predicted on the basis of the information provided by increasing the number of looks, the results of this study were examined in light of the results of Hafter and Dye (1983). If increasing number of looks were responsible for better lateralization performance and the information provided by increasing number of looks were being integrated optimally, the slope of the function on log-log coordinates should be -0.5. When slopes were computed over a number of looks encompassing the range used in

Hafter and Dye (1983), the slopes of the 3-component functions were steeper than would have been predicted based on optimal integration of information and the slopes of the 5-component functions were shallower than would have been predicted based on optimal integration of information. Slopes computer over a range greater than that used in Hafter and Dye (1983) were shallower than predicted for both 3- and 5-component stimuli. The fact that slopes were steeper than predicted for 3-component stimuli and shallower than predicted for 5-component stimuli indicated that lateralization performance was not determined solely by number of looks. Lateralization performance could also have been affected by the rate at which the looks occur and the effective modulation depth of the stimulus envelopes. If increasing modulation frequency only increased the number of looks, subjects' sensitivity should increase. However, increasing modulation frequency also increases the rate at which the looks are arriving and increasing the rate decreases the subjects' sensitivity. Therefore, in terms of sensitivity, there is a trade off between the number of looks and the rate at which the looks arrive. Given this trade off, the Hafter and Dye (1983) data suggest that we might expect to see a small net increase in sensitivity as modulation frequency increases. We see this happening in these data. Furthermore, studies such as Hafter and Dye (1983) which use filtered clicks show that, in general, subjects have lower threshold ITDs than those seen for fixed phase stimuli used in this study. Likewise, the threshold ITDs for fixed phase stimuli are lower than the threshold ITDs for random phase stimuli in this study. This suggests that modulation depth also influences sensitivity. That is, as modulation depth increases, so does the subjects' sensitivity. Based on these results it was concluded, as did McFadden and Moffitt (1977), that although number of looks at the stimulus envelope plays a role in the improvement of lateralization performance, number of looks alone does not explain the improvement in lateralization performance for moderate modulation frequencies.

Figures 1-4 show that the effects of phase-randomization tend to be confined to low modulation frequencies, which is consistent with the notion that phase effects should only be present when components are unresolved. These results do not appear to support the conclusions drawn by Henning (1980) that binaural models such as Blauert and Cobben's do not account for lateralization of high-frequency, amplitude-modulated waveforms on the basis of interaural envelope delay. These data fail to support Henning for three reasons: First, Henning (1980) concluded that performance with QFM waveforms was not as poor as would have been expected on the basis of simple envelope detection, however, he did not specify how we might estimate the expected magnitude of the effect of reducing a waveform's modulation depth. Second, the Blauert and Cobben model assumes that binaural processing of the extracted envelopes occurs within, not across, matched auditory channels. Henning (1980), however, used modulation frequencies in the vicinity of 300 Hz which according to Patterson's (1976) estimates of auditory filter shape would fall at the 6 dB down points of the auditory filter. At these higher modulation frequencies, the outermost components of the waveform are 6 dB down and the model says nothing concerning how envelopes might be extracted when these components are attenuated. Finally, in this study we do see an effect of phase-randomization or reduction in effective modulation depth at low modulation frequencies when the components of the stimulus fall within the critical band of the auditory filter.

Randomizing the starting phases of the stimulus components reduces the effective depths of modulation of the stimuli while minimizing the frequency sweeps inherent in FM and QFM. Because the notion of simple envelope extraction is so central to contemporary binaural theory, it was hoped that a stimulus manipulation could be devised that more severely and more systematically limited the envelope fluctuations of the temporal waveform without introducing smooth changes in the short-term frequency-domain representations of the signal. The magnitude of some of the results of this study raise the concern that perhaps phase-randomization is not sufficiently potent in its effect on the temporal envelope. In conducting this study, it was noted that many of the random-phase waveforms produced oscilloscope tracings that appeared to be very peaky. Since Nuetzel and Hafter (1981) found that reducing the modulation depth of SAM tones had little effect until the modulation depth dropped below 0.5, it is possible that perhaps the effective depth of modulation of the stimuli was not sufficiently reduced in some cases.

Results also showed that subject performance with 5-component stimuli was better than that obtained with 3-component stimuli. This was especially true at the lower modulation frequencies where all components interact resulting in greater amplitude excursions. Another possible reason for better performance with 5-component stimuli is that these stimuli have a greater effective depth of modulation, on the average, than 3-component stimuli. If, as the Blauert and Cobben model assumes, binaural processing of the extracted envelopes occurs within a channel, then 5-component stimuli with low modulation frequencies should show a decrease in threshold ITD due to the increase in effective depth of modulation. If we define a channel as the critical bandwidth of the auditory filter centered at the carrier frequency, then at higher modulation frequencies only the middle three components of the 5-component stimuli fall within a channel and effective modulation depth is not increased, ergo no significant decrease in threshold ITD is predicted.

According to Patterson's (1976) estimate of auditory filter shape, the auditory filter centered at the 4000 Hz carrier frequency used in this study should be symmetrical and would have 6 dB down points at 3700 and 4300 Hz. This corresponds very well to the data presented here. The effect of adding components to the stimulus is greatest at or below the 200 Hz modulation frequency for all four subjects. In the 5-component condition, a modulation frequency of 300 Hz produces components which fall outside the 6 dB down points of the filter whereas a modulation frequency of 200 Hz or less yields components which fall within the 6 dB down point of the filter. When additional frequency components fall within the 6 dB down points of the filter, the effective modulation depth of the stimuli increases and the Blauert and Cobben (1978) model predicts an increase in sensitivity. The data, therefore, support this prediction of the model.

In summary, the effects of phase-randomization support Blauert and Cobben's basic tenet of cross-correlation of the outputs of matched envelope extractors. However, it is difficult to ascertain whether the effects of phase-randomization on the effective depth of modulation are sufficiently large to result in a loss of synchronization by the auditory system. After all, cross-correlation itself is phase insensitive. Furthermore, the proposed envelope extractor easily accounts for the decreased sensitivity found in other studies and for the effect of number of stimulus components found in this study. In addition to this, envelope extraction is consistent with what we know about peripheral auditory physiology and alternative envelope extraction mechanisms are scarce. To this extent the model is still a powerful conceptual tool for studying binaural processing.

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APPROVAL SHEET

The thesis submitted by Andrew J. Niemiec has been read and approved by the following committee:

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The final copies have been examined by the director of the thesis and the signature which appears below verifies the fact that any necessary changes have been incorporated and that the thesis is now given final approval by the Committee with reference to content and form.

The thesis is therefore accepted in partial fulfillment of the requirements for the degree of Master of Arts.

Oct. 27, 1988
Date

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