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Negating the Effects of Binaural Cues: Competition Between Auditory Streaming and Contralateral Induction

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When a pair of monaural pure tones, A and B, are repeatedly alternated in one ear, with noise bursts presented in synchrony with B in the other ear, the noise sometimes delateralizes B. This is presumably a case of Warren and Bashford's (1976) contralateral induction effect. However, the present experiment shows that the degree of contralateral induction is proportional to the separation in frequency between A and B. It was also found that the degree to which the noise bursts influenced B's timbre was proportional to the separation in frequency between A and B. The combined results suggest that cues that govern the sequential organization of sounds influence the use of binaural cues not only during the assignment of position to auditory events but during the assignment of timbre.

The neural pathways that carry information about the locations of sound sources appear to be anatomically separate from the pathways that carry information used to discriminate sounds (Evans, 1974; Evans & Nelson, 1973a, 1973b). These findings, along with behavioral evidence that shows that the appropriate stimuli can cause a sound at one ear to be incorrectly assigned the pitch of a sound at the other ear (Deutsch & Roll, 1976) have led to the conclusion that at some levels of the auditory system, localization cues act independently of cues used in assigning identities to stimuli (e.g., Deutsch, 1980).

However, evidence also exists to suggest that at later stages in the system, the processes that assign identities and positions to events must act interdependently. One process known to influence the perceived identity of successive acoustic events (by organizing such events into perceptual units) is that which Bregman and Campbell (1971) called *auditory stream segregation* (now shortened to *streaming*). Streaming refers to the tendency for successive tones that are similar in frequency to attract each other into a single perceptual unit, or stream. When such attractions operate between the tones of a sequence containing a bimodal distribution of frequencies, the sequence splits into two streams so that listeners report the experience of two separate sources of sound. In a normal auditory environment such effects might contribute to the "parsing" of individual sound sources from complex acoustic mixtures that arise when several sources are simultaneously active. Bregman (1978b) conceived the sequential attraction evident between successive tones at a similar frequency as a perceptual process that takes advantage of the fact that when a rapid sequence of sounds with similar frequencies arrives at the ear, it is likely to have arisen from a single sound source. A sequence of sounds containing events at widely different frequencies, on the other hand, is likely to have been due to the mixture of elements from two or more sources.

The present authors have recently documented the notion that streaming and vertical localization interact in auditory perception (Bregman & Steiger, 1980). Our experiments took advantage of the fact that as a sound's spectrum becomes higher in fre-

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quency, it is localized in progressively higher spatial positions (Pratt, 1930; Roffler & Butler, 1968). In one experiment, we presented pairs of noise bursts along the midsagittal plane in a free field, each burst accompanied by a synchronous pure tone (heard over acoustically transparent headphones). We found that the perceived vertical location of each burst was strongly correlated with the pitch of the accompanying tone. Presumably, this was due to the fact that the tones fused perceptually with the noise bursts (because of the synchrony of their onsets and offsets). Such fusion would alter the noise spectra and the consequent localization of the noise based on these spectra. However, we also found that when each tone was preceded and followed by identical tones (placed in the silences before and after each noise burst), the influence of the tones on the perceived locations of the bursts was diminished. We accounted for this effect by arguing that in the latter case, the successive tones attracted each other into one perceptual stream, whereas the bursts tended to form a separate stream, so that the tones fused less with the bursts. Consequently, the tones made a lesser contribution to the spectrum of each burst and had less influence upon the bursts' perceived position. Therefore in this experiment, a process that affected the perceived identity of each burst (i.e., streaming) also appeared to influence the perceived location of the burst.

Deutsch (1975) has also reported an apparent effect, active in the horizontal plane, of streaming on localization. She presented a dichotic stimulus composed of simultaneous ascending and descending musical scales so that the successive tones of each scale alternated between the ears. Most listeners heard as being in the same ear those tones that were proximal in frequency, despite the fact that the tones had originated in two different ears. Thus, a grouping by frequency had apparently affected the perceived location of some of the tones. A similar effect is reported by Butler (1979). These results suggest that streaming may influence the localization of tones at the two ears by creating a pressure toward localizing the elements of a single auditory stream at a single position in space.

The current experiments sought to further examine the relation between streaming and localization in the horizontal dimension. To achieve this end we manipulated a localization cue based solely on interaural intensity differences by using an effect that Warren and Bashford (1976) have named "contralateral induction." In this effect, the perceived laterality of a monaural pure tone (say, at the left ear) becomes displaced toward the side of a simultaneous contralateral noise burst (say, at the right ear), providing that the noise is sufficiently intense and contains energy at the same frequency as the tone. Similar induction effects have been observed with tones presented over a monaural headphone in synchrony with a contralateral noise in the free field (Butler & Naunton, 1962) and with monaural speech presented with a contralateral noise (Egan, 1948). Presumably, contralateral induction results because energy from the noise, which matches the frequency of a target signal and is contralateral to it, provides an interaural cue that promotes the localization of the target in a less lateralized position.

The question of interest in the current study was whether or not we could vary the induction of a pure tone toward a contralateral noise by manipulating a tendency for the tone to be drawn into an auditory stream in a manner that was antagonistic to the attraction of the tone toward the contralateral noise burst. We based the design of our stimuli on the supposition that we could reduce the weighting assigned to interaural cues (which presumably cause contralateral induction to occur) by introducing cues that favored the organization of the components of sound at each ear into separate monaural streams. The general stimulus pattern that we used is shown in Figure 1. All stimuli were dichotic. A monaural target tone (B) was presented with a synchronous noise masker in the opposite ear. The target (B) and masker pair were repeatedly alternated with a second monaural tone (A), variable in frequency. Tone A was always presented to the same ear as Tone B. The continuous alternation of these stimuli was intended to promote sequential streaming between A and B, since Bregman (1978a) has shown that information favoring streaming be-

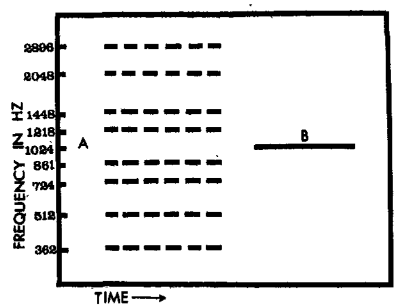

Figure 1. A representation of the stimuli presented to the left ear in all experiments. (A captor tone [A], variable in frequency, was alternated with a target tone [B]. The various captor [A] tone options used are shown in dotted lines. Note that each dotted line represents a continuous 100-msec captor tone. In synchrony with the target [B], a noise masker, not depicted in the figure, was presented to the right ear. The figure shows one cycle of a continuously repeated pattern.)

tween tones accumulates over repeated presentations of cyclical stimuli. As A was made progressively closer in frequency to B, we expected that it should begin to "capture" B into a sequential stream. (For this reason, A will be referred to as the *captor.*) We presumed that the sequential attraction between A and B might compete with and overcome the "contralateral attraction" from the noise masker. If so, then, the contralateral induction effect should become weaker as the sequential A–B attraction became stronger. Such a result would suggest that streaming directly influenced the perceived laterality of B by overriding the contribution made to B's perceived position by interaural intensity cues. In turn, this result would provide additional support for the notion that streaming and localization are interdependent. The first experiment reported below examined the effects of such monaural streaming between A and B on the strength of the contralateral induction acting on B. A second experiment used a similar design to examine the influence of streaming on an interaural effect in which the timbre of B was influenced by contralateral noise.

Experiment 1

Listeners heard dichotic stimuli containing tones and noise bursts. They were asked to record the position in which they heard the tones in each stimulus by selecting numbers appropriate for the position of each tone from a chart that showed an outline of a head divided into 12 equal, numbered divisions (along the interaural plane). The positions on the extreme left and right were numbered 1 and 12, respectively.

Method

Subjects

Twenty volunteers were recruited from the McGill University graduate and undergraduate student body. All listeners reported having normal hearing.

Stimuli

All stimuli consisted of 100-msec pure tone bursts and 100-msec bursts of noise. Each noise burst consisted of a roughly one-octave band centered at 1024 Hz, with a rolloff of 48 dB/octave at both the upper and lower cut-off frequencies. All events had roughly exponential rise and decay times of 10 msec.

Most of the stimuli in this experiment were based on the schematic shown in Figure 1. They consisted of a captor (A) and target (B) tone pair, continuously alternated in the left ear. Tones A and B were separated by 30 msec of silence, and the successive A–B pairs were separated by 232 msec of silence. The longer silence between cycles was designed to facilitate the identification of the position of the two tones, A and B, within the cycle. Tone B was always presented with a contralateral noise masker (not shown in Figure 1). To manipulate the frequency proximity, and hence the tendency for streaming to occur between the captor and target tones, the frequency of A was varied in eight steps, between 362, 512, 724, 861, 1218, 1448, 2048 or 2896 Hz, respectively. Tone B was always constant in frequency at 1024 Hz. Tone A was thus most likely to stream with B when at the middle range of frequencies. We expected that across these eight conditions, the closer A came in frequency to B, the weaker would be the contralateral induction effect on B and the stronger B's tendency to remain lateralized on the left.

We included two additional stimuli that contained the target and masker but no A tone. In one, called *isolated target*, continuous repetitions of the dichotic target/masker pair were presented to enable us to evaluate the size of the contralateral induction effect in the absence of any influences of streaming on B. In the other, called *two burst*, the dichotic target/burst pair was repeatedly alternated with a second monaural noise burst. Both bursts were presented to the right ear. It was presumed that if successive noise bursts are able to form a sequential stream (as do successive pure tones), then the perceptual effect on the perceived position of B should be similar in this condition to that of the conditions in which a captor tone (A) was close in frequency to B. In both cases, the sequential attraction between events in a monaural stream (either Tones A and B on the one hand, or the two bursts on the other) might compete with the interaural influence between B and the simultaneous noise masker. We expected that contralateral induction effects should be attenuated in both types of conditions.

In the isolated-target condition, the rate of repetition of the dichotic target/burst pair was identical to that in the stimuli containing captor tones, with a 100-msec silence replacing the captor tone. Similarly, the temporal relations between events in the two-burst condition were identical to those in the captor-tone stimuli. All tones were matched for approximately equal loudness to a 1024-Hz reference tone presented at 60-dB SPL, using Fletcher-Munson (1933) equal-loudness curves.[1]

One hundred and fifty cycles of each of the 10 stimuli described above were recorded on each of four different stereophonic tapes, with tone bursts always on the left track and noise bursts always on the right. On each tape, the trials were in random order, with the exception of the isolated-target and two-burst conditions, which were always presented as the 9th and 10th trials, respectively, in each block of 10. This was done to avoid confusing the listeners who would have to localize only one tone on the latter trials but two tones on the former. Each subject was tested in four sessions employing four different tapes. In each session, the noise masker was set at one of four different levels of intensity: 70-, 75-, 80- or 85-dB SPL. Under the assumption that contralateral induction is due to interaural intensity cues, the higher noise levels should have caused stronger induction of B toward the noise by introducing greater amounts of energy at the ear opposite B. Thus, by comparing the results at different noise levels we could determine whether or not any reported delateralization of B was in fact due to contralateral induction.

In addition, a tape containing sets of pure tones designed to be heard as lateralized in any one of five different positions was prepared for training the listeners. The tones were recorded in stereo at five different interchannel intensities so that they would appear to have arisen from one of several different locations when heard binaurally. On a second tape six practice stimuli, representing the range of stimuli containing A and B tones described above, were recorded. However, the tone bursts and noise bursts in the practice stimuli were shifted to frequencies unlike those used in the experimental conditions to avoid specific carry-over effects. In a pretest, the practice stimuli were judged to produce similar contralateral induction effects to the experimental stimuli.

Procedure

Instructions. Listeners were tested individually in an audiometric chamber. With written instructions and diagrams, the experimenters informed the listeners that they were participating in an experiment concerned with the localization of tones in noise. They were told that they would hear repeating patterns of two tones, A and B, with a noise burst synchronized with B, or repetitions of one tone also presented with a noise burst. They were instructed to record the locations of tones A and B, or of the single tone B on each trial, by writing the number appropriate for the location of each tone on their response sheet in boxes labeled "First Tone Location" and "Second Tone Location." The response sheet contained a third response slot for each trial, which listeners were told to tick if the noise prevented them from hearing Tone B at all. To reduce the difficulty of the task, listeners were informed that Tone B would always appear in the same location as A, or to its right. They were also informed that only one tone (B) would be present in the 9th and 10th trials of each block of 10 trials. On each trial, the listeners were told to allow a sufficient number of repetitions of each stimulus to be played to permit them to make a reliable judgment. They were then allowed to advance the tape to the next stimulus (by pressing a button provided for that purpose).

Training. The training tape (see the Stimulus section) was played for each listener. The approximate position of the set of tones in each of the first five stimuli was described by the experimenter, who indicated the position predicted by the particular interaural intensities at which each set was presented. The remaining 12 training stimuli were then presented, and listeners were required to call out the number (from the 12-position chart described in the introductory remarks on this experiment) that corresponded to the position in which each tone was heard. If listeners' judgments were grossly different from those that were predicted by the interaural disparities present in each stimulus, the experimenter offered corrective feedback by suggesting a more appropriate (although approximate) location. The six practice trials (see the Stimulus section) were then presented, and each listener was again asked to judge the positions of the tones in each stimulus. This time, however, no feedback was given so as to avoid biasing the listeners to learn any response set to differences in the stimuli along frequency or other dimensions. In these latter stimuli, the noise bursts were initially set to the second-to-highest level used in experimental sessions. If a listener found it difficult to hear both tones on his/her first exposure to the stimuli, the noise levels were attenuated until the tones became more clearly audible and then were raised back to the original level.

Testing. The listeners received four test sessions each. In each session a different tape (containing 10 trials) and a different noise level was used. The serial order in which tapes and noise levels were used across the four sessions was random, with the restriction that each tape and each noise level was used equally often in each serial position across all listeners. Short breaks (approximately 2 min.) were provided between each block of 10 trials.

Apparatus

The stimuli were synthesized digitally (at a 10000-Hz sampling rate) on a Digital Equipment Corporation PDP-11/34 computer, using the MITSYN software package (Henke, 1975). Stimuli were output on two channels of the computer's digital-to-analog (D/A) converter and recorded on stereo audiotapes using a Marantz SD-9000

[1] Due to an oversight in loudness compensation, a monotonic error was introduced such that the lowest captor tone was about 4 dB too intense, the error decreasing with increasing frequency. However, only the lowest two captors deviated by more than 1 dB from the equal-loudness values indicated by the Fletcher-Munson curve. The loudnesses of the targets in all conditions were, of course, identical, since the frequency of the targets was not varied.

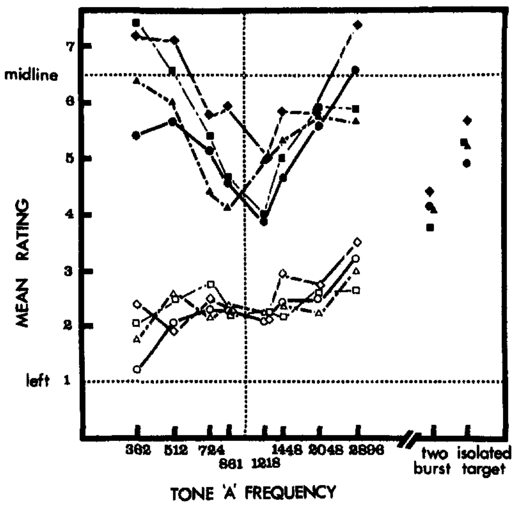

Figure 2. Mean perceived positions of Tone B (solid symbols) and Tone A (open symbols) at each captor frequency. (The curves resulting from each noise level condition are plotted separately. The mean values on two-burst and isolated-target conditions at each noise level are shown on the right. A value of 1 represents a tone heard as lateralized to the left and a value of 6.5, a tone heard at the midline. Circle = 70-dB mask; triangle = 75-dB mask; square = 80-dB mask; diamond = 85-dB mask.)

programmable stereo cassette deck. The deck provided a feature that allowed listeners to advance the tape from trial to trial once they had responded. During recording, the channel carrying sinusoidal stimuli was low-pass filtered at 4.5 KHz with a Rockland 851 filter to remove digitization noise. The other channel, which carried wide-band noise output by the D/A, was band-pass filtered through a cascaded pair of Rockland 851 filters, one set to high-pass filter at 724 Hz and the other set to low-pass filter at 1448 Hz. In this manner, what was registered on the tape was an approximately one-octave band of noise centered at 1024 Hz. A General Radio type 1551-C sound-level meter with a flat-plate coupler was used to measure the levels of all stimuli. The signals were amplified and played back over Sennheiser HD-424 headphones. One channel (that carrying the noise-burst stimuli) was passed through a General Radio step attenuator prior to amplification so that the noise level could be controlled in stepwise increments. The other channel, carrying the tone bursts, was passed through an ADC stereo frequency equalizer prior to amplification to allow for equal loudness compensation and for compensation of the frequency response of the playback equipment.

Results

Figure 2 shows the mean perceived laterality of Tones A and B at each noise-burst level and for each captor condition. The value 1 represents a tone that is lateralized completely to the left, and 6.5 represents a tone heard at the midline.[2]

Tone B Data

A clear influence of the frequency proximity between Tones A and B on the size of the contralateral induction effect on B is visible in the curves for the conditions containing captor tones, showing as a smooth U-shaped curve when plotted as a function of captor frequency. The target (B) is perceived to be progressively less lateralized as the difference in frequency between A and B becomes larger. A quadratic trend analysis performed on the overall means for the conditions containing captor tones showed the curvilinear trend to be highly reliable, $F(1, 145) = 27.95$, $p < .0001$.[3] The main effect of captor condition (which included the two-burst and isolated-target conditions) was also highly significant, $F(9, 145) = 5.19$, $p < .001$. The difference between the isolated-target and two-burst conditions was also tested on a planned comparison and found to be significant, $F(1, 145) = 5.04$, $p < .05$. Thus, in the isolated-target condition, Tone B was rated as less lateralized than it was in the two-burst condition, in which B was judged to be quite lateralized. Although higher than that of the two-burst condition, the isolated-target condition yielded a value that appears to fall in a somewhat intermediate position relative to the means for the other conditions. The isolated-target condition mean was tested against the combined means for the conditions with the largest differences in frequency between A and B (i.e., those that yielded the highest values), and it was found to be significantly lower, $F(1, 145) = 7.05$, $p < .01$.

The values in Figure 2 show a somewhat ambiguous effect of different noise-burst levels on the laterality of Tone B. However, the higher levels do appear to yield generally less

[2] The standard deviations about the means shown in Figure 2 ranged from 2.05 to 3.53. There were no systematic differences between the standard deviations in different conditions.

[3] To compensate for missing observations 26 degrees of freedom were subtracted from all error terms.

lateralization of B than do lower levels, with overall means for the 70-, 75-, 80- and 85-dB noise levels being 5.07, 5.22, 5.39, and 6.00, respectively. The main effect of the noise-level factor was significant, $F(3, 31) = 3.48$, $p < .05$. The interaction of captor and noise-level factors was nonsignificant.

Tone A Data

The curves for the judgments of the position of Tone A suggest that Tone A (which had no accompanying noise) was always heard in a lateralized position (see Figure 2). It appears, however, that the higher frequency captors tended to be heard as slightly less lateralized than did the lower frequency captors. This difference showed in the analysis of Tone A scores as a significant main effect of the captor frequency, $F(7, 133) = 2.49$, $p < .025$. No other effects were significant.

Discussion

The effects observed in this experiment can be accounted for by assuming that two antagonistic forces acted to yield B's perceived position in each condition: (a) a *contralateral attraction* exerted by the noise masker on B, and (b) a *sequential attraction* exerted by A on B (when they were in close frequency proximity), which promoted the perception of B as part of the same stream and as having a similar location as A. The fact that higher noise levels yielded a greater delateralization of B confirms that the force active in delateralizing B was contralateral induction. That successive tones that are close in frequency attract each other sequentially is a well-documented tendency (e.g., Bregman, 1978a, 1978b). We suggest that these two organizing principles were traded off against each other, so that when the A–B organization was strong it contributed much more heavily to the final percept of B's location than did the binaural influence from the noise burst on B. Conversely, when the A–B organization was weak (when A and B were far apart in frequency) binaural evidence was given primacy. As a result, the target shifted to a more centered position on the basis of binaural intensity cues. A similar argument may also account for the fact that the target in the two-burst condition was perceived in a lateralized position. A strong sequential organization between the successive noise bursts may, again, have overpowered the binaural effect of the noise on the contralateral target tone.

We offer the preceding explanation with one reservation, however. In the absence of any sequential attraction, the target in the isolated-target condition should have been perceived as more delateralized than in any other condition. For in this condition, we should have seen the strongest effects of contralateral induction acting on B with no competing influence from a captor tone. Figure 2 shows that this result did not occur. Instead the target was rated as delateralized only to an intermediate degree. Given this result, we cannot rule out the alternate possibility that B was perceived as relatively delateralized in conditions in which A and B were far apart in frequency because it was repelled by captors that had dissimilar frequencies (rather than being attracted by captors with similar frequencies). However, we prefer the account that considers the effect of the captor to be one of attracting (vs. repelling) B for several reasons: (a) It is not unlikely that judgments of the position of the target in the isolated-target condition were biased toward the lower end of the scale because the tone was judged in the absence of a clearly lateralized event that could be used to anchor the listener's spatial reference (i.e., Tone A). As a result, the judgments of stimuli containing only one tone on each cycle may have required absolute judgments, whereas the stimuli containing A and B tones may have required only relative judgments (even though an absolute scale was used to register these judgments). The results on the two types of stimuli may thus not be directly comparable. (b) Although the literature on perceptual organization contains many references to phenomena involving mutual attractions between tones (e.g., Bregman, 1978a, 1978b), no evidence is available to suggest that tones repel each other.

We offer no explanation for the observed tendency for Tone A to have been perceived as less lateralized when high versus low in

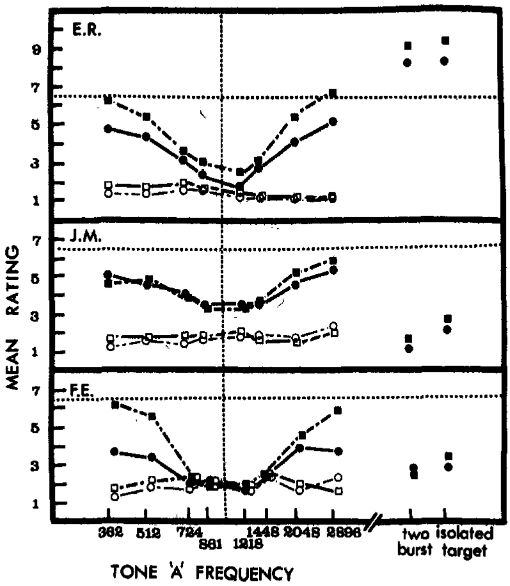

Figure 3. Mean perceived positions of Tone B (solid symbols) and Tone A (open symbols) at each frequency for listeners ER, JM, and FE. (The two lowest [70 and 75 dB] and two highest [80 and 85 dB] noise levels have been averaged together and plotted as circles and squares, respectively. The mean values on two-burst and isolated-target conditions for the higher and lower pair of noise levels are shown on the right.)

frequency. This effect is a small one, however, and does not influence our interpretation of the main effects of interest (i.e., the effects of captor frequency and noise level on the laterality of Tone B).

Experiment 2

This experiment was similar to Experiment 1, employing identical stimuli and apparatus. It was performed to enable us to collect a larger amount of data from a few listeners so that we could examine the quantitative features of the observed effects with more precision.

Method

Subjects

Three listeners were recruited and paid for their participation in the experiment. ER was a highly trained 27-year-old listener who had considerable experience in research in binaural phenomena and many years of musical training. He had also participated as a listener in Experiment 1. Listener JM was 23 years old and had previously participated as a subject in several auditory experiments, none of which were concerned with auditory localization. He was also trained in music. Listener FE was 24 years old and was completely untrained in auditory phenomena or in music.

Procedure

The training and treatment of subjects was identical to that in Experiment 1. In the current experiment, however, subjects heard each of the 40 stimuli (10 patterns with noise bursts at 4 levels) six times. The resulting 240 trials were divided into 24 blocks of 10 trials, so that each block consisted of the 10 possible patterns heard with the noise at a single sound pressure level. A different randomization of conditions was used in each block and for each listener. However, isolated-target and two-burst stimuli were (as in Experiment 1) always presented as the 9th and 10th trials, respectively, in each block of 10.

Results and Discussion

Figure 3 shows the mean judgments by each of the three listeners of the positions of Tones A and B in each of the conditions containing Tone A, as well as those of Tone B in the isolated-target and two-burst conditions. Note that the ordinate is more compressed than in Figure 2. For the sake of clarity, the values for the two lowest (70 and 75 dB) and highest (80 and 85 dB) noise levels have been collapsed. Each value thus represents the average of 12 observations. The data from all three listeners show an effect of A's correspondence in frequency to B on the perceived laterality of B similar to that observed in Experiment 1. The effect of the noise level factor is, with the exception of the data for listener JM, much more pronounced than the corresponding effect observed in the previous experiment. The general pattern of these results again leads us to suggest that the induction of B toward the contralateral noise burst was traded against a sequential attraction between Tones A and B to arrive at a perceptual location for Tone B.

There is, however, some inconsistency between the listeners' ratings of B's position in the isolated-target and two-burst conditions. Although the isolated-target condition appears to have generally yielded somewhat higher (i.e., less lateralized) scores than the two-burst condition (a pattern consistent with the predictions and findings of Experiment 1), listener ER's ratings of both conditions are very high (i.e., delateralized), whereas those of listeners JM and FE are very low (i.e., lateralized). However, it was suggested previously that the isolated-target and two-burst conditions may have required absolute judgments of B's laterality, whereas the other conditions may only have required a judgment of B's position relative to A. Therefore we can perhaps account for these intersubject differences by the fact that ER was a much more trained listener than were the others and as a result may have provided better absolute judgments of B's position in the conditions lacking a captor tone.

Nevertheless, this does not question the differences observed between the conditions containing captor tones. These latter effects may be attributed directly to an influence of the proximity in frequency between tones A and B on the perceived laterality of B.[4]

Experiment 3

During pretesting for these experiments, it was observed that not only did a monaural noise burst serve to induce a contralateral tone to be heard in a more medial position but also that it affected the perceived timbre of the tone. As the inducing noise was made louder, we noticed that the tone began to assimilate some of the noiselike properties of the noise burst, making a transition from pure in quality to a quality resembling that of colored noise. Presumably, this was because binaural pathways permit some of the perceptual properties of the tone and noise to blend across the ears. We reasoned that much as our previous experiments had shown an effect in which a monaural perceptual stream (between A and B) could essentially "disengage" binaural influences on the perceived location of individual elements of that stream, we could show a similar effect of such a stream on binaural influences from noise in one ear on the perceptual quality (timbre) of elements of a stream in the other ear.

To test this hypothesis, we ran an experiment that used identical stimuli to those of Experiment 1 (the same tapes prepared for that experiment were employed). In this study, however, listeners controlled the level of the noise bursts themselves by adjusting a control knob. Their instruction was to listen first to the alternating pair of tones, A and B (or the repeating Tone B in the isolated-target and two-burst conditions), and then to introduce the noise gradually until they noticed that B became impure. We predicted that the threshold for this judgment would be higher in conditions in which A and B were closer in frequency. Such a result would suggest that when B grouped into a monaural stream with A, it was also freed from influences on its timbre from the contralateral noise. The result would therefore lend additional support to the conception that sequential organization interacts with the use of binaural information. Furthermore these results would not be predictable on the assumption that the listeners would detect a change in B's timbre by using A as a standard of pure-tone quality. In this case, the closer the frequency of A and B, the more sensitive the comparison should be and the lower the level of contralateral noise required to "color" B's timbre. We predicted the opposite result, a greater coloring of B's timbre when A was further away in frequency.

Method

Subjects

Although this experiment is reported separately here, it was conducted in a single session following the four sessions reported in Experiment 1 above. The data reported here were thus collected from the same group of listeners who participated in that experiment.

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[4] We have several reasons for believing that the loudness compensation error mentioned in Footnote 1 did not bias the results of the experiments reported above: The error was monotonic (i.e., it was largest at the low frequency end of the range employed) and could not, therefore, have produced the curvilinear trends evident in our data. In addition, the curvilinearity is clearly visible in the data even if the suspect pair of low frequency captors is ignored. Nevertheless, as an extra safeguard we conducted a follow-up experiment in which three observers were tested using the same stimulus tapes described in the text, with noise bursts presented at 85 dB. Each listener judged each stimulus twelve times, six times with the loudnesses of all tones correctly calibrated and six times with the overcompensation described in Footnote 1. The predicted curvilinear trend showed clearly in both compensation conditions, suggesting that the data reported above is reliable and undistorted by the compensation problem.

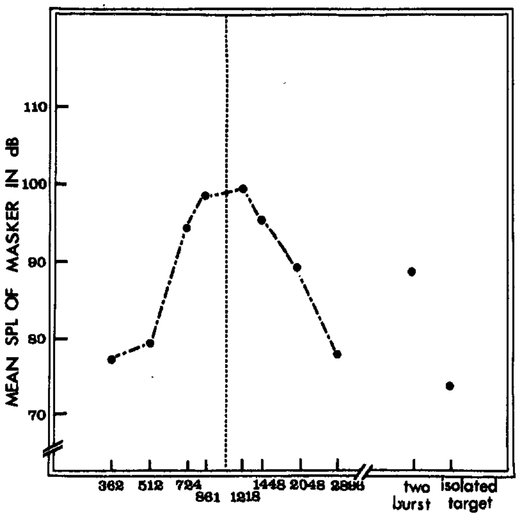

Figure 4. Mean sound pressure level (SPL) to which the noise masker was adjusted in each condition, as a function of captor frequency. (The means for two-burst and isolated-target conditions are shown on the right.)

Stimuli

All stimuli were identical to those used in Experiment 1.

Procedure

Listeners were told to begin each trial with the control knob (which controlled the noise level), in the "off" position. They were told to raise the noise level gradually until they noticed that the tone they heard in synchrony with each noise burst began to sound impure. At that point the listeners were instructed to record the voltage level visible on the multimenter. The response sheets also contained a blank for each trial labeled "Tone B never became impure." Listeners were told to tick this blank if (a) Tone B remained pure-sounding even at the highest level of the noise stimulus, or (b) Tone B eventually became masked by the noise but remained pure until the masking level. In the former case, listeners were also told to record the value that showed on the meter at the maximum setting of the control knob, and in the latter they were told to record the level at which the tone became masked by the noise. Thus we could discriminate these two perceptual effects in the data. The six practice trials (described in Experiment 1) were then presented. No feedback was given on this practice session. Listeners were then tested with one of the four randomizations of the 10 conditions.

Apparatus

The apparatus used to present stimuli was almost identical to that described in the previous experiments. However, in place of the step attenuator, a stereophonic preamplifier was introduced at the output of the channel of the tape deck carrying the noise signals. The gain control on this preamplifier was used to vary the noise-burst levels continously. A continuous signal, fed through the preamplifier's other channel, was read on a digital multimeter. Since the preamplifier's gain controlled both channels, changes in the voltage read on the meter corresponded to changes in the level of the noise signals and provided a reference from which we could easily determine the sound pressure level of the noise signals at any setting of the gain-control knob.

Results and Discussion

The voltage levels recorded by listeners on each trial were converted to decibels (of noise mask) and subjected to a one-way analysis of variance. One subject neglected to record levels on three trials that received "Tone B never became impure" ratings. The values for these trials were estimated with cell means. In compensation, all effects were tested on appropriately reduced degrees of freedom.

Figure 4 shows the mean sound pressure level to which the noise had to be raised in each condition to produce a noticeable influence on the purity of the target tone (B). It is clear from the results that a much higher noise level was required to affect B's quality when it was preceded by a captor at a similar frequency. The main effect of the captor factor was highly significant, $F(9, 168) = 10.86$, $p < .0001$. A quadratic trend analysis performed on the means for the conditions containing A tones was also significant, $F(1, 168) = 67.08$, $p < .0001$. In addition, it should be noted that in the current experiment, the two-burst condition required a noise burst almost 30 dB louder than B to affect B's quality, whereas the isolated-target condition required the noise to be little more than 10 dB more intense than B itself before an effect on B's purity became evident. Thus, on the purity judgment, the single-tone stimuli conform closely to our expectation about the strength of binaural effects on these conditions; that is, the isolated-target condition, which was expected to reflect the effects of interaural influences on B with no competition from a captor tone, showed a strong influence of the contralateral masker on B's quality, whereas the two-burst condition, in which the potential for streaming between the successive pair of noise bursts was expected to act antagonistically toward interaural influences, showed a weaker effect of the masker on B's quality.

Recall that listeners stopped raising the noise level at the point at which B became masked, even if B remained pure until that point. Therefore, it is possible that the low levels in Figure 4 might simply reflect the fact that in some conditions B was easily masked by the noise. However, if this were so, then the conditions that yielded low mean decibel levels should also have yielded the greatest number of ratings of "Tone B never became impure" (since the listeners were told to use this rating if Tone B remained pure until the masking level). The results do not confirm this conjecture. For the eight captor conditions shown in Figure 4, with Tone A frequencies running from 362 Hz to 2896 Hz, the numbers of listeners (out of 20) who reported that "Tone B never became impure" even at the highest masker level were 1, 5, 5, 12, 7, 7, 4, and 2. Five listeners reported that B never became impure in the two-burst condition, and no listeners reported this result in the isolated-target condition. From these values, it can be seen that the conditions that yielded higher rather than lower mean decibel values yielded correspondingly high numbers of cases in which B remained pure throughout the trial. Therefore we can attribute the curve for the mean levels of noise in different conditions directly to the fact that the quality of the target (B) was influenced by the noise to different degrees in different conditions.

The results of this experiment therefore provide a second line of evidence to support our initial hypothesis that cues favoring the sequential organization of monaural events will reduce the effect of interaural cues that might otherwise be dominant. In isolation, a monaural noise burst influences the perceived purity of a contralateral pure tone (B). However, its effect is greatly attenuated when B is drawn into a stream with a preceding monaural tone A presented to the same ear as B, or when the burst is drawn into a stream with a preceding ipsilateral burst. We therefore again find support for the premise that the sequential attraction between tones close to each other in frequency competes with the effects of binaural information.

The results of the current experiment clearly indicate that the effect had by the streaming of Tones A and B when they were close in frequency was one of reducing the strength of binaural influences on B. Recall that the results of Experiments 1 and 2 taken alone left some ambiguity as to whether it was the attraction between A and B when they were close in frequency that competed with binaural influences on B's location, or a repulsion between A and B when they were far apart in frequency that added to the binaural effect. Given the results of Experiment 3, we are encouraged to favor the former account.

General Discussion

The results of the experiments reported above indicate that the principles governing the sequential organization of auditory events (i.e., streaming) also influence the weighting assigned to interaural cues active during the perception of the events. Consider the relations between streaming cues and interaural cues that appear to have been responsible for the effects observed in Experiments 1 and 2. Apparently the sequential attraction between Tones A and B opposed the effect of a contralateral noise burst on the perceived laterality of Tone B. How might the opposition of such cues act to provide a more reliable perceptual image in a normal environment? One might propose the following: When an event (B) on one side of the head is heard with a loud contralateral noise, the auditory system is faced with the possibility that the noise might have masked energy from B, arriving at the same ear as the noise. Hence, by estimating the location of the event as being in a less lateralized position than the monaural registration of B's energy would suggest, the system may often compensate for the effects of such masking, making the resulting localization a more reliable one. Such a proposal was put forward by Warren and Bashford (1976) in discussing the functional significance of contralateral induction. However, if B is strongly linked perceptually to an earlier occurring and clearly lateralized Event A that has been heard in the absence of any simultaneous noise, then A provides a "glimpse" of the probable location of B. Given that A is clearly located to one side, the probability becomes high that B is on that side as well, and therefore the induction of B toward the noise mask is undesirable. Thus, to optimize the localization of any event (in particular an event heard in a noisy context), binaural evidence favoring the assignment of a particular location to the event should be traded off against evidence concerning how the event integrates perceptually with other more clearly localizeable sounds. Presumably, the results of such a trade-off can account for the effects evident in our experiments.

The results of Experiment 3 suggest that another influence of streaming may be to eliminate interaural effects on the timbre of auditory events. As the target B was more strongly drawn into a stream with the captor A, B's timbre appeared to be less easily influenced by a contralateral noise burst. Possibly, the effect depended upon a general tendency for the less clearly heard elements of a stream to assimilate the properties of the more clearly heard elements. If so, the calculation that determined B's perceptual quality may have been more strongly biased in favor of keeping the quality of B close to that of A whenever B was more strongly linked perceptually with A. When the pressure to maintain such congruence between the timbres of A and B was sufficiently strong, it may have acted to negate binaural influences (from the noise) on B's timbre. A similar tendency for the timbres of tones in dichotic sequences to be rearranged in accordance with their assignment to perceptual units on the basis of frequency proximity has been reported by Butler (1979). Whether or not our explanation is correct, our data suggest that streaming influences the use of evidence from the binaural system not only during the assignment of position to events but also during the assignment of timbre.

These results in turn suggest that to refer to binaural mechanisms as "the localization system," as is commonly done, is incorrect. The use of the term in this manner ignores the contribution made by data from other systems (among them the streaming system) to the assignment of position to auditory events. Furthermore, binaural cues are known to influence sequential organization (Judd, 1979). Therefore, like the streaming system, the binuaral system also appears to contribute to both identity and localization decisions. This evidence suggests that it is appropriate to characterize the binaural and streaming systems as mechanisms that collaborate toward the generation of an integral, localized image of environmental sounds.

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