Lateralization thresholds obtained under conditions in which the precedence effect is assumed to operate[a)]

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(Received 10 August 1989; accepted for publication 22 November 1989)

Interaural differences of time (IDT) thresholds were measured with 600-μs transients. The initial experiment was a successful replication of previous experiments that have obtained the precedence effect in lateralization paradigms (e.g., Yost and Soderquist, 1984). When a dichotic click followed a diotic click with an interclick interval (ICI) less than 1 ms or larger than 5 ms, IDT thresholds were generally less than 40 μs. For ICIs between 1 to 5 ms, IDT thresholds increased to approximately 220 μs. Poorest performance was observed for ICIs of 1.75 to 2.35 ms. During the course of conducting a series of planned experiments on this effect, a substantial drop in IDT thresholds was observed across the ICIs of maximum interest (1 to 5 ms). The precedence effect, which we had replicated in our initial experiment, essentially "disappeared" when the subjects were given sufficient practice on the lateralization task. A number of conditions were explored in an unsuccessful attempt to recover the precedence effect in these experienced subjects. The implications of these results are discussed.

PACS numbers: 43.66.Qp, 43.66.Pn, 43.66.Mk [WAY]

INTRODUCTION

When the human auditory system encounters two successive and temporally proximate binaural events, the localization of the resultant fused image is said to be largely determined by the directional cues associated with the first-arriving acoustic wave front. The inability of the auditory system to appreciate echoes in reverberant surroundings, despite hundreds of otherwise audible, and at times more intense, reflections (i.e., additivity of multiple secondary wave fronts), is cited as a stunning example of this localization illusion in operation. This well-known phenomenon has come to be termed the precedence/Haas effect in sound localization (Wallach *et al.*, 1949; Haas, 1951).[1]

Minimum audible angle (MAA) experiments at our laboratory have already demonstrated the possibility of extracting localization information from later-arriving events, and, thus, demonstrating the failure of the precedence effect, at least in a spatial acuity task (Perrott *et al.*, 1989). Unlike the original studies of Wallach/Haas in which the effect was shown to operate up to azimuth angles of 60 deg, we were able to demonstrate that *localization acuity* was relatively unimpaired. MAA thresholds ranging from 3–7 deg were observed under what we believed to be optimal conditions for obtaining the effect.

It has become increasingly clear to us that the specific features of the test procedures are probably critical in determining whether or not one observes the precedence effect in the free field. In our work, the "echo" was treated as an event to be detected. The subject's task was to identify which of several sources had generated the "echo" on that trial. Feedback, and therefore practice, was possible. Such paradigms are commonly encountered in psychoacoustic experiments that attempt to establish the operating limits of the auditory system. One can imagine that quite a different description of frequency resolution or masking would be exhibited if a paradigm similar to those that have been generally employed in the precedence effect literature had been employed on the latter problems.

The precedence effect has also been studied in lateralization paradigms. In addition to the superior stimulus control that can be afforded under earphone listening conditions, substantially more rigorous psychophysical methods have generally been used (e.g., Zurek, 1980; Yost and Soderquist, 1984). Since our initial attempt to replicate the precedence effect in the free field was relatively unsuccessful, we thought that the lateralization paradigm might provide a better opportunity to examine this interesting phenomenon in detail. The initial experiment was initiated simply to replicate the precedence effect in the lateralization paradigm.

I. REPLICATION OF THE PRECEDENCE EFFECT IN A LATERALIZATION PARADIGM

A. Method

1. Subjects

Four subjects, two males and two females, from California State University, Los Angeles, including the authors, served in experiment I. All subjects had previous experience in lateralization tasks. Three of the subjects had previous experience in a precedence effect experiment conducted in the free field. All subjects had normal hearing based on self-report.

2. Apparatus.

A pair of multifunction signal generators (Wavetek, model 184) was used to generate 40 μs square-wave pulses.

[a)] Portions of this paper were presented at the 117th Meeting of the Acoustical Society of America, Syracuse, NY [J. Acoust. Soc. Am. Suppl. 1 85, S84 (1989)].

The output of each generator was fed directly into an earphone (TDH 49). Measures of the acoustic output of the earphones [using a sound-level meter (GenRad) connected to a 6-cc coupler and a 10-MHz dual channel storage oscilloscope (TEKTRONIX SC 503)] indicated that the transient had a duration of 600 μs. A spectrum analysis (Hewlett–Packard, model 3582 A) of the outputs of the two signal generators indicated no discrepancy between these devices. Signal level was set at 60 dB (A-weighted). All aspects of the experiment were under the direct control of a microprocessor. With this system, IDTs could be varied in steps of 2.5 μs, starting from a minimum of 7.5 μs.

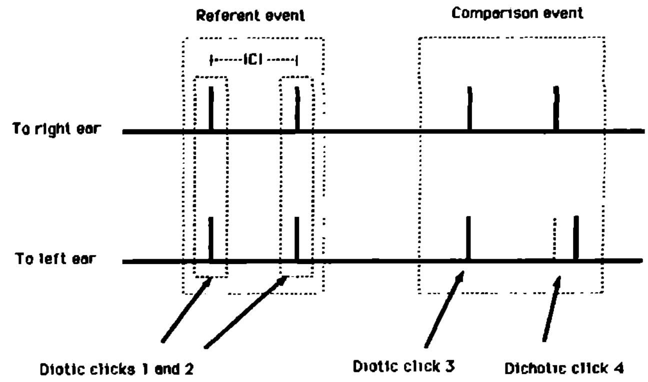

FIG. 1. Configuration of click presentations. The referent was always centered on the median plane. The comparison was separated from the referent by 300 ms. In the condition depicted here (condition I), the second click of the comparison event was dichotic, while the first was diotic ("echo" condition). In condition II (not shown), the second click of the comparison was diotic, while the first was dichotic.

3. Procedure and psychophysical method

Subjects were briefed on the experiment and experimental procedures and received 5–20 practice sessions before actual data collection began. At the beginning of each session, diotic transients were presented to subjects over the earphones at a rate of 1 Hz. The subjects were asked to adjust the headphones until the signals appeared to be in the center of the head. This was done to provide acoustic balance at the entrance of the ear canals, since imbalance could occur for such reasons as asymmetries in the listener's head or acoustic leaks at the headphone cushions (Domnitz, 1975).

Once balance was achieved, subjects pressed a response key to initiate the session. The configuration of event presentations is diagrammed in Fig. 1. Each trial involved the presentation of four binaural clicks. The first two, presented with an ICI of between 0.38 to 10 ms, were always diotic (IDT = 0). This pair of clicks represented the "referent event" against which the second pair of clicks would be compared. The referent event was identical to the second pair of clicks in every aspect except that no IDTs were available. For the range of ICIs employed, subjects typically reported hearing a single "fused" image. Some variation in extensity was evident with larger ICIs, and two events could at times be discerned at these larger intervals. After a 300-ms interpulse interval, the comparison binaural click pair was presented. Both clicks of the referent event were always diotic (IDT = 0). The comparison event, however, could follow one of two configurations. In condition I, the IDT for the second click of the comparison event could vary, while the IDT for the first click of the comparison event was zero (this configuration is depicted in Fig. 1). In condition II, the IDT for the second click of the comparison was zero, while the IDT for the first click of the comparison could vary (not shown). The two conditions were run in separate sessions.

In condition I, we were, in effect, measuring the subject's capacity to resolve the spatial information contained in the "echo." What subjects heard on each trial of this condition were two brief events, separated by 300 ms. The first of these was always centered at or near the median plane (center of the head), while the second might be perceived laterally (either to the right or left of the head on a random basis) according to IDTs associated with the second click of the comparison event. The subject's task was to indicate whether the second event was to the right or left of the first (a 70.7% criterion was employed).

In condition II, the ability to use the spatial information in the direct or first-arriving wave front was measured. If the precedence effect was to operate, then one should observe much larger IDT thresholds in condition I than in condition II.

A two-down, one-up adaptive paradigm (Levitt, 1971) was used. The IDT was varied in 10-μs steps during the first 20 reversals. In the second 20 reversals, IDT was varied in 5-μs steps. For the remaining 60 reversals, the step size was reduced to 2.5 μs. The IDTs obtained in the last 60 reversals were averaged to generate one estimate of threshold. Within a session, only one ICI and one condition were tested. Multiple sessions were completed by each subject on each condition. Threshold estimates were thus based upon the performance obtained over at least two sessions (120 reversals). Subjects received feedback as to whether they were correct immediately after each response.

B. Results

In condition I (optimal conditions for the demonstration of the precedence effect), IDT thresholds were strongly dependent on the temporal separation of the two component clicks in the comparison event. Figure 2(a) summarizes these data. For ICIs smaller than 1 and larger than 5 ms, IDT thresholds obtained were relatively small and constant at approximately 25–45 μs. For ICI values between 1 and 5 ms, however, thresholds increased precipitously, reaching approximately 220 μs for ICIs between 1.75–2.35 ms. This tenfold change in the IDT threshold for a narrow range of ICIs is a clear replication of the effect reported by earlier investigators. The results of condition II are presented in Fig. 2(b). With the dichotic click leading the diotic, the IDT thresholds obtained were independent of ICIs (and quite small, ranging from 15–25 μs).

The results from both conditions I and II are similar to those obtained by Zurek (1980), Gaskell (1983), and Yost

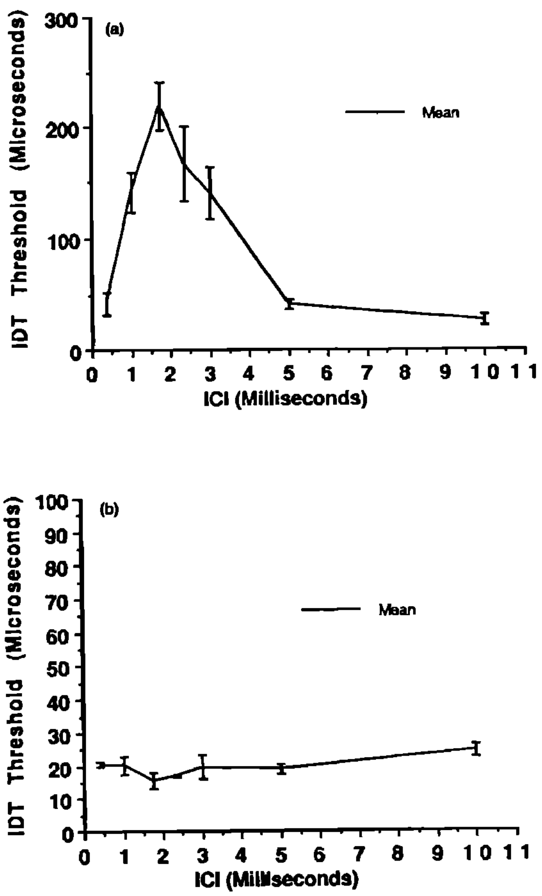

FIG. 2. (a) Mean IDT thresholds obtained for the "lag" event. Poorest performance was observed for "lead–lag" separations of 1 to 5 ms. (b) Mean IDT thresholds obtained for the "lead" event. Performance was independent of lead–lag separations. Error bars represent 1 standard deviation.

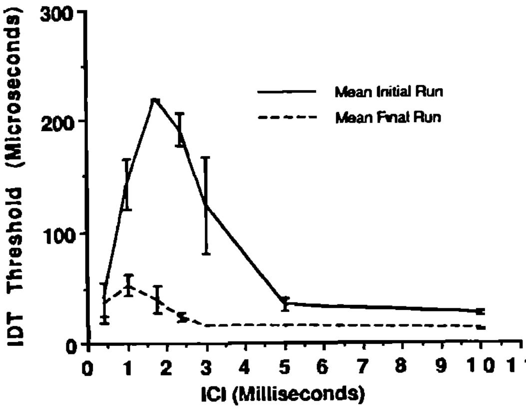

FIG. 3. Improvement in performance for experienced subjects. Top curve is the original data obtained from three subjects before the extended practice sessions. The bottom curve was obtained after several weeks of practice. Error bars represent 1 standard deviation.

and Soderquist (1984), although, generally speaking, we did observe somewhat lower thresholds. These lower thresholds could possibly be accounted for by the "center-left" versus "center-right" method employed, which is an easier procedure than the typical "side-center" versus "center-side" paradigm.

II. SOME *POST HOC* EXPERIMENTS

A. Overview

During the course of conducting a number of subsequent experiments, which we had specifically designed to study the characteristics of the precedence effect,[7] we encountered a rather curious problem. We did not seem to be able to obtain a stable estimate of the IDT threshold, even under conditions optimal for the demonstration of the precedence effect. The tenfold increase in the IDT threshold observed in experiment I when the diotic click led the dichotic by 1.75–2.35 ms gradually began to decline. This slow but persistent improvement in performance was not only puzzling, but troublesome, particularly since it was observed in all of our subsequent designs and across all our subjects. We halted these new experiments and decided to rerun the first experiment.

B. Method

1. Subjects

Three subjects, one male and two females, served in this experiment. Two of the subjects (KS and VC) had completed the first experiment and had served in at least one of the follow-up experiments. The third subject (LD) had participated in our follow-up paradigms. The two original subjects had served 20 and 12 h, respectively, and the third subject had served 8 h, on the lateralization task prior to beginning the current experiment.

2. Apparatus and procedure

Both the apparatus and the procedure employed were the same as described in the first experiment. The initial performance on the condition in which the diotic click led the dichotic for ICIs ranging from 0.38–10 ms was already available for the first two subjects. We collected data using the same procedure for the third subject (LD), and defined this and the original data for subjects 1 and 2 as the initial baseline. Each subject then entered a practice phase. The ICIs were set at values corresponding to the temporal window of interest (1–5 ms) with the most emphasis on ICI = 2.35 ms. The subjects were run on these conditions for at least 30 min per session until IDT thresholds stabilized. Once stabilization was achieved (i.e., less than 20% variation on the last three runs), a final baseline for ICIs varying from 0.38 to 10 ms was collected. The subjects completed the practice phase of the current experiment with less than 10 h of training.

C. Results

The results of this experiment supported our initial observations. The magnitude of the effect for all subjects was substantially lower after the subjects had completed the testing procedure (see Fig. 3). Although there is still somewhat of a residual effect evident, its magnitude is extremely small. Further, for the ICI that subjects had practiced most (2.35 ms), the effect is practically nonexistent. The shift in the peak of the function from 1.75 to 1.0 ms could possibly be attributed to the fact that subjects practiced the 1.0-ms condition much less than the other conditions (1.75–2.35 ms) that had previously yielded the largest thresholds.

Having lost the precedence effect, we began an extensive series of experiments on these practiced subjects in an attempt to once again find the effect. While the initial tests were conducted with 40-μs square-wave transients, we applied brief (single-cycle) sine-wave pulses ranging in frequency from 250 Hz to 12 kHz, but without success. Again, with the brief transients, we examined intensity levels ranging from 45–110 dB (A-weighted), but still no recovery of the function was evident. Finally, in our search for the lost effect, we were able to discover a very specific condition where the effect could once again be demonstrated. The initial 40-μs transient, when passed through a 4-kHz high-pass filter, resulted in IDT thresholds in excess of 150 μs. This latter effect, however, was also quite transient. After a few practice sessions, thresholds again dropped to below 30 μs.[3] For one subject, we deliberately withheld practice for over 3 months with no trials in this or any other lateralization experiment. Still, after this period, there was no evidence of the recovery of the initial effect.[4] One additional point should be made in this regard. Considering that most of our subjects' now considerable experience on the task was restricted to a single condition, whatever they learned apparently could be readily generalized to the other stimuli employed.

III. ADDITIONAL CONTROL EXPERIMENTS

The addition of IDTs to ICIs causes the potential of a monaural spectral cue based on whether a particular click at a particular ear is leading or lagging the other click presented to the other ear. If the IDT is added to the ICI, the result could be the sensation of a lower pitch, and, if it is subtracted from the ICI, the result could be the sensation of a higher pitch (Yost, 1982). To ensure against monaural pitch cues, the following control experiments were conducted.

A. Study I

1. Method

a. Subjects. Two of the practiced subjects (LD and KS), for whom IDT thresholds had substantially decreased in the precedence effect paradigm, served as subjects.

b. Apparatus and procedure. All apparatus and procedures were the same as condition I of experiment I (dichotic lagging), with the following changes. Only one ICI was used (2.35 ms). To effectively control for any monaural effects, the subjects were simply tested on the same task and on the same apparatus and paradigm, *monaurally* (right ear), the argument being that, if subjects were using monaural pitch shifts, then performance in the monaural condition should approximate that of the binaural condition. Subjects were instructed to use any possible cue (e.g., pitch, location, duration, etc.). Feedback was provided immediately after every trial. Data were collected in five sessions. In order to compare these data with those of the binaural condition, we also retested the same subjects using the original paradigm (condition I of experiment I, binaural at an ICI of 2.35 ms). During each run, subjects were tested on only one condition. The order of testing between conditions was completely randomized.

2. Results

Figure 4 presents the results of the monaural control condition versus the original binaural condition for the two subjects. Thresholds under the monaural condition could not be measured since their magnitude was larger than our apparatus could measure (in excess of 250 μs). Under the binaural condition, thresholds ranged from 15–27 μs. This disparity in performance between monaural and binaural conditions provides evidence against the effective utility of monaural spectral cues in experiment I. Furthermore, in order to ensure that *binaural* pitch artifacts were not involved, we decided to conduct a second control experiment.

B. Study II

1. Method

a. Subjects. The same two subjects from study I were used in study II.

b. Apparatus and procedure. All apparatus and procedures were the same as condition I of experiment I, with the following changes in paradigm. The new configuration of click presentation is diagrammed in Fig. 5. In order to prevent subjects from comparing pitch differences between the referent and comparison events, we eliminated the second diotic click from the referent event. The referent thus became a single diotic click. The ICI for all runs of this experiment was set at 2.25 ms with a $\pm$ 0.25-ms ($\pm$ 11%) temporal jitter from trial to trial. With the addition of this temporal jitter, the ICI on any one trial could be selected randomly and with equal likelihood from a pool of 120 possible ICIs (a range of 2.25 $\pm$ to 0.25 ms). The largest magnitude of this jitter was 20 times the magnitude of the IDTs added to the monaural channels at threshold, therefore obscuring any added monaural change. IDTs were kept independent of this jitter and varied according to the adaptive paradigm described. Thresholds were also obtained monaurally under

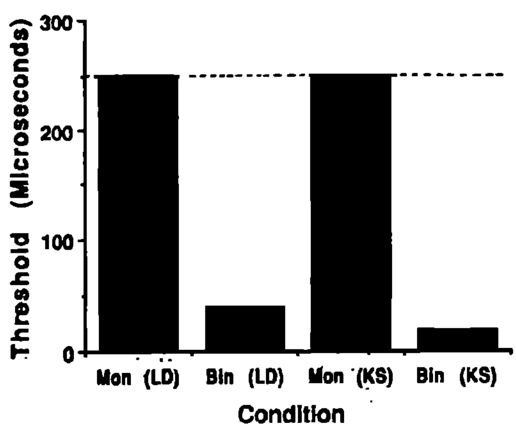

FIG. 4. Results of control study I (ICI = 2.35 ms). Monaural performance for both subjects under the original paradigm of experiment I is significantly poorer than binaural performance under the same paradigm. The dashed line represents the limits of our system. The shaded area represents 1 standard deviation.

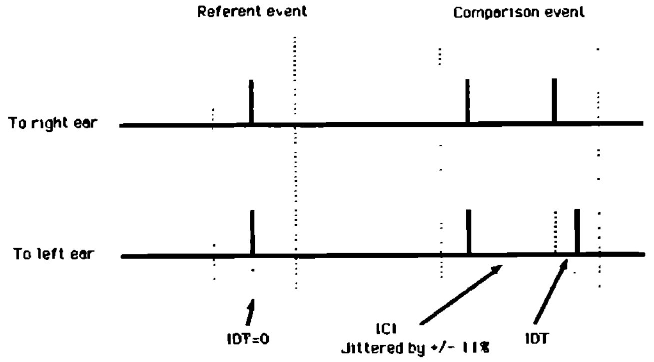

FIG. 5. Configuration of click presentations in the binaural control condition of study II. The referent image in this paradigm was modified to a single binaural click. In addition, the ICI (2.25 ± 0.25 ms) of the comparison event was jittered from trial to trial by ± 11%.

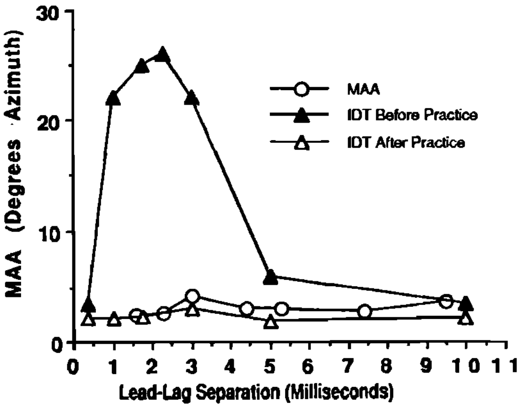

FIG. 7. Original (top curve) and final lateralization thresholds obtained for subject KS translated into azimuthal angles. Angular separations observed for this subject after practice match the MAA thresholds obtained for the same subject in a localization study of the precedence effect (Perrott *et al.*, 1989).

this new paradigm to control for any monaural effects in the control binaural condition. Data were collected in five sessions for each of the control binaural and monaural conditions. The order of testing was randomized across sessions.

2. Results

Figure 6 presents the results of control study II for both subjects. Binaural performance under pitch control conditions supports the results of monaural testing in control study I. Here, again, monaural thresholds were unmeasurable, and binaural performance ranged from 20–25 μs.

IV. DISCUSSION

The results of our current set of experiments are similar to those of our previous experiments on the precedence effect in a localization task in which MAA thresholds of between 3 to 7 deg were observed. Figure 7 is a plot of the MAA thresholds for subject KS (Perrott *et al.*, 1989) compared to the lateralization thresholds obtained for the same subject in the current experiments translated into azimuthal angles (Woodworth and Schlosberg, 1954). It is fair to note that the primary difference that we have observed between localization and lateralization performance was that the latter task required extensive practice before performance finally stabilized.

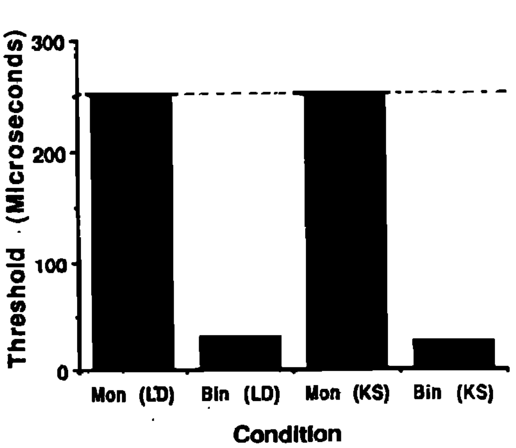

FIG. 6. Results of control study II. No significant differences were observed between the original biaural (Fig. 4) and control binaural paradigms. Monaural performance was equally poor in both studies I and II. Shaded area represents 1 standard deviation.

The present results indicate that, if the conditions are optimal, a substantial loss in the ability to utilize IDT can be observed in the second of two nearly simultaneous binaural events (a replication of the precedence effect). But we do not believe that this loss in resolution is indicative of any underlying inhibitory process *per se*. Whatever information is contained in the lag event must surely still be available to our subjects. Given sufficient experience on the task, thresholds are elevated by only a few microseconds over those encountered when a single dichotic event is present. Possibly, what is most surprising is the fact that, once the subject is able to resolve IDTs in the second event, this skill can be readily generalized to a wide variety of signals. Moreover, although we have data on only one subject, this experience can be retained for many months without difficulty.

If the information from the later-arriving event is not suppressed, why do less experienced subjects show the precedence effect? We believe that a process analogous to the problem of *hidden figures* seen in the visual modality may be responsible. By way of example, a line drawing of George Washington, which when presented upon a homogeneous background can be readily recognized, can be nearly impossible to detect if it is incorporated into another figure (i.e., as part of a tree or a cloud). On the other hand, the drawing of George Washington, once located, is readily identified. Clearly, the figure is neither "masked" nor "inhibited." The precedence effect then is probably related to the process by which the nervous system develops order from an array of information.[5] One model, the sensory rivalry hypotheses (Hafter *et al.*, 1988), suggests that the system simply organizes the information based upon the most probable structure. The information in an echo then is simply incorporated into the resulting image and not suppressed. Such a system would be far more adaptive than one that automatically suppresses echoes. For example, in the case of motion (the issue that initially stimulated our interest in this process), later-arriving information may be readily utilized once sufficient information has occurred to identify that the source or the listener is in motion. That is, the solution of the most probable case may define how the information is organized and ultimately how it is employed.[6]

ACKNOWLEDGMENTS

This research was supported in part by grants from the National Science Foundation (BNS-8512317) and the National Institutes of Health (3S06-RR0801-1452).

[1]For an historical account, see Gardner (1968).

[2]Two new paradigms were to be investigated. The first was a three-click paradigm in which we used a primary conditioner (diotic click) to suppress a secondary conditioner (a second diotic click) and measured spatial sensitivity in a third probe (a dichotic click with a variable IDT, as used in the first experiment). The interval between the second diotic click and the dichotic click was set at 2.35 ms, the optimal ICI for the demonstration of the precedence effect in the first experiment. The ICI between the first and second diotic clicks was varied from 0.38 to 30 ms. Results showed a U-shaped function demonstrating a reduction of the precedence effect when the secondary conditioner was presented within 10 ms of the primary conditioner. The second paradigm was a click train paradigm in which all events were separated by 2.35 ms. We measured the subject's sensitivity to a dichotic probe located at various positions within this pulse train. Results indicated a precipitous drop in the precedence effect the further the probe was from the onset of the train within three to four intervals. Our interest in these effects declined, however, as it became increasingly clear that performance continued to improve over the course of these tests.

[3]The 4-kHz high-pass signal used here was a much weaker and significantly different signal that could possibly account for the temporary threshold elevation. In the course of these experiments, we examined various types of stimuli with long-duration (3 to 4 ms) low-pass and short-duration (less than 1 ms) high-pass and various bandpass configurations, with no success of recovering the precedence effect. Initially, we had generated signals directly from the computer through pulse formers when we first noticed the decline in thresholds. In order to control for possible artifacts, we added the multifunction signal generators. The current set of data was obtained with the latter devices. The ability of our subjects to resolve the task with the wide variety of filtered and unfiltered clicks not only argues against learning to cue on a specific signal artifact; it also suggests a skill that can be readily generalized to a wide variety of transient events.

[4]One of the authors (DRP), who had not received the extensive exposure to the task, still continued to show a strong "precedence effect" during this period of testing. Naive listeners tested also continued to behave as the literature predicts. Thus we felt reasonably confident that nothing had happened to our stimulus over the course of these experiments.

[5]One subject (LD), after completing a session in which she obtained an IDT threshold in excess of 150 μs, was informed that subject KS had solved the "problem" by focusing on the microstructure of the image. The simple knowledge that the task could be resolved seemed to have an immediate benefit. In the following run, her thresholds dropped to less than 70 μs. Such effects seem to be far more characteristic of a cognitive (organizational) process being involved than reflective of some underlying sensory mechanism.

[6]This view of the perceptual process is counterintuitive since it argues that what is perceived is based upon what decision has been reached regarding what has actually transpired. If two sources are activated in sequence and the temporal order is within critical limits, the subject perceives a single moving sound that seems to travel from the first to the second source (apparent motion). Note that the information as to whether the space to the right or left (up or down) of the first source would contain an image was not available until the second event was already present (Perrott *et al.*, 1987).

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