Restarting the adapted binaural system[a)]

Ervin R. Hafter and Thomas N. Buell[b)]
Department of Psychology, University of California, Berkeley, California 94720

(Received 2 May 1989; accepted for publication 9 March 1990)

Previous experiments using trains of high-frequency filtered clicks have shown that for lateralization based on interaural differences of time or level, there is a decline in the usefulness of interaural information after the signal's onset when the clicks are presented at a high rate. This process has been referred to as "binaural adaptation." Of interest here are the conditions that produce a recovery from adaptation and allow for a resampling of the interaural information. A train of clicks with short interclick intervals is used to produce adaptation. Then, during its course, a treatment such as the insertion of a temporal gap or the addition of another "triggering" sound is tested for its ability to restart the binaural process. All of the brief triggers tested are shown to be capable of promoting recovery from adaptation. This suggests that, while the binaural system deals with the demands of high-frequency stimulation with rapid adaptation, it quickly cancels the adaptation in response to stimulus change.

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

INTRODUCTION

A. Binaural adaptation

Listeners can detect interaural differences of time (IDTs) in the onsets of signals throughout the audible spectrum, but in order to extract IDTs from the remainder of the stimulus, successive peaks in the waveform must occur at a rate that is not too high. For pure tones, it must be below 1200–1500 Hz; for delays in the envelope peaks of sinusoidally modulated high frequencies, the rate must not exceed about 400/s (Nuetzel and Hafter, 1981). In a study of lateralization with trains of high-frequency clicks, Hafter and Dye (1983) examined the relation between onset and ongoing binaural information by measuring the relative effectiveness of each individual click in the train. Of interest were both the interclick interval (ICI) and the number of clicks in the train n. They applied a "method of subtraction," which attributes differences between thresholds for trains of different lengths to information derived from the additional clicks in the longer trains. The argument assumes that detection of laterality is based on the averaged activity of the set of binaural neurons responsible for comparing the timing of events in the two input channels and that there are N such neural events on which a given judgment is based. Note that N is the sum of the events evoked in each neural single channel integrated across all of the relevant channels. A second assumption is that the limitation on detection is set by a background of temporal noise or "jitter" that perturbs the timing of the N samples. Since the standard deviation of the mean IDT is proportional to the square root of the number of samples on which it is based, one should expect the threshold, as defined by a fixed mean-to-standard deviation ratio d' to decline as the inverse square root of N:

$$\Delta\text{IDT} \propto (N^{0.5})^{-1} . \tag{1}$$

One would like to study the efficacy of each click by direct observation of the number of neural events evoked by the train but, of course, that is impossible. However, the link between threshold and N can be inferred from the results of increasing n. Hafter and Dye (1983) showed that many of the models commonly used to describe the effects of increased stimulus rate, including refractoriness, increased bandwidth, and serial correlation of the internal noise, all call for an essentially linear relation between N and n. Thus they predict proportionality between threshold and $1/(n)^{0.5}$, regardless of the rate. With this in mind, those authors plotted log thresholds versus log n for a range of ICIs, with the expectation that the slope would be -0.5 as indicated by a square-root relationship. Instead, what appeared was a series of straight lines in the log–log plots, with absolute slopes that diminished toward zero with decreased ICIs:

$$\log \Delta\text{IDT}_n = \log \Delta\text{IDT}_1 - 0.5k \log (n) , \tag{2}$$

with $0 \leqslant k \leqslant 1$ and $k = f(\text{ICI})$. The antilogarithm shows

$$\Delta\text{IDT}_n / \Delta\text{IDT}_1 = [(n^k)^{0.5}]^{-1} . \tag{3}$$

This implies that the relation between the number of effective neural responses and the number of clicks in the train is a compressive power function whose exponent declines with the rate of stimulation (1/ICI):

$$N \propto n^k . \tag{4}$$

One can define the *relative effectiveness* of the jth click in a train as the difference between the N_j produced by a train of length n_j and the N_{j-1} produced by a train of length n_{j-1}. Figure 1 shows hypothetical results of this computation for a series of values of the parameter k ranging from 0.0 to 1.0. The ordinate plots:

$$\text{relative effectiveness} = (n_j)^k - (n_{j-1})^k . \tag{5}$$

The uppermost function ($k = 1$) is for the case when the ICI

[a)] Portions of the data were first presented at the Spring 1985 Meeting of the Acoustical Society of America [J. Acoust. Soc. Am. Suppl. 1 77, S49 (1985)].

[b)] Current address: Center for Neurological Sciences, University of Connecticut Health Center, Farmington, CT 06032.

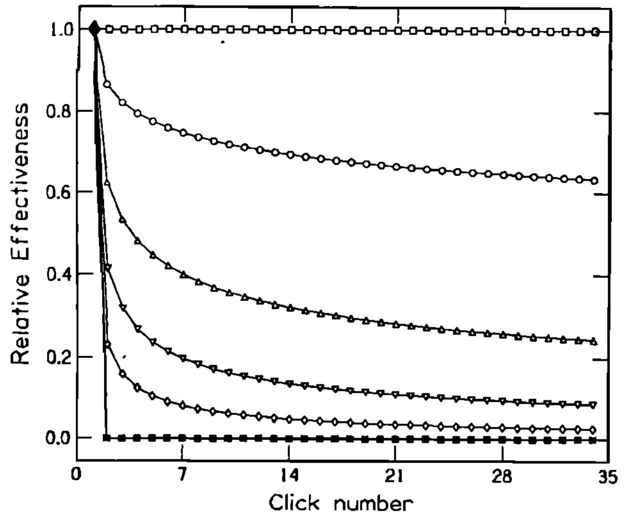

FIG. 1. *Relative effectiveness* [see Eq. (5)] of successive clicks in a train as calculated in Eq. (5) for values of k ranging from 0 to 1. Connecting lines are included only to aid visualization. The uppermost function represents a case with long ICIs where each click in the train is equally effective. The lowermost is for the case with a very short ICI; there, only the first click in the train is effective.

is very long while the lowermost ($k = 0$) represents very short ICIs. The ordinate is normalized to the value for a single dichotic click to remove the physical units. Effectiveness is computed only for integer values of n, but lines are drawn to facilitate identification of functions representing the various values of k. One might wish to think of these as post-stimulus time (PST) histograms of the kind used to describe the responses of single neurons; if so, then the uppermost is often referred to as a "tonic" response while the lowermost is called "phasic." This family of curves shows that as the rate of stimulation increases, the binaural response becomes more phasic, i.e., more reliant on information in the onset (Buell and Hafter, 1988). The logic behind the technique is discussed in detail in Hafter and Dye (1983), where the rate-dependent loss of information after the onset is called "saturation." We now prefer the term "binaural adaptation" (Hafter *et al.*, 1988).

B. Recovery from adaptation

Given that the binaural response to sounds with a high envelope rate depends mainly on information derived from the signal's onset, one might ask, "Under what conditions is there a recovery from adaptation sufficient to allow a *restarting* of the binaural process in which there is *resampling* of the acoustic environment?" Obviously, this must happen after a sufficient period of nonstimulation and the idea of the first experiment was to discover how long the temporal gap must be in order to induce restarting.

I. EXPERIMENT 1: RESTARTING WITH GAPS

A. Rationale

The technique is illustrated in Fig. 2. The upper half shows the time-domain waveforms for (a) an unbroken train of 6 clicks, (b) an unbroken train of 12 clicks, and (c) a train of 12 clicks with a gap inserted in the middle. The drawing shows only the signals presented to one ear; those to the other ear were delayed by an IDT.

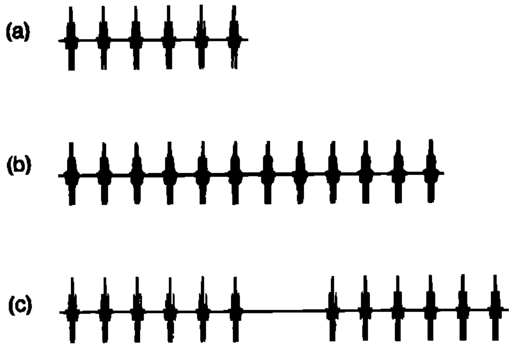

FIG. 2. Waveforms used in experiment 1. Only the stimuli to one ear are shown. The individual clicks have center frequencies of 4000 Hz. The ICI is 2.5 ms. The gap introduced in the center of train (c) is 7.5 ms.

The expected result of this experiment is schematized in the log–log plots in Fig. 3. The ordinate is plotted in units of relative threshold, that is, the threshold for n clicks (ΔIDT_n) divided by the threshold for a single click (ΔIDT_1). The dotted line drawn through the point for $n = 1$ has a slope of -0.5 ($k = 1.0$) indicative of an inverse square-root decline, i.e., no adaptation. The hypothetical data marked by the squares represent relative ΔIDTs for trains (a) and (b); the fact that the slope ($-0.5k$) of the best-fitting line is more shallow than the dotted line shows the presence of adaptation. Suppose that the gap in the train of 12 clicks (c) provokes complete recovery from adaptation. Then the two half-trains should transmit as much information as two independent sets of $n = 6$, predicting a threshold of

$$\Delta IDT_{6,2} = \Delta IDT_6/(2)^{0.5}. \quad (6)$$

Again, the inverse square-root relation between thresholds (for one and two sets of six clicks) can be seen from the slope (-0.5) of the short dashed line drawn to the open square at $n = 12$. Following similar logic, one should be able to break

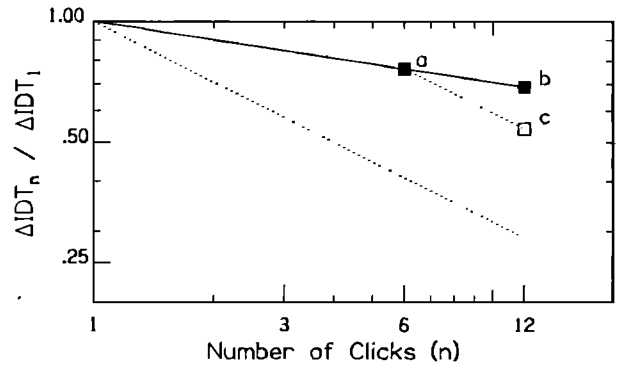

FIG. 3. The expected outcome of experiment 1 given that the gap provokes recovery from adaptation. The hypothetical data points are labeled to represent the conditions shown in Fig. 2. The dotted lines have the slope of -0.5 that is indicative of a square-root decline. Point c shows the predicted result if the gap causes complete recovery, leading to a threshold for two sets of six clicks that is 1/2 times the threshold for a set of six alone.

a train at any location(s) by one or more gaps and compute the expected performance based on the sum of the information in the individual segments.

B. Procedure

Each click was produced in the time domain by multiplying a 4000-Hz sinusoid—the carrier frequency—by a Gaussian function centered at the cosine phase of the carrier. Clicks were calculated in a PDP-11/34 computer and presented dichotically with 14-bit digital-to-analog converters at a rate of 50 kHz through Frequency Devices No. 901F 48-dB/oct, low-pass filters set to 20 kHz. The digital amplitude of the click was chosen to utilize the entire ± 13 bits of excursion, with voltages represented by less than 1 bit being truncated to zero. The duration of the points between terminal zero values was 2 ms. The duration between the $\pm 1\sigma$ (standard deviation) points was 0.455 ms; the amplitude and power spectra of single clicks were also Gaussian, centered at 4000 Hz, with widths between $\pm 1\sigma$ points of 1400 and 989 Hz, respectively.

During the set-up period before each set of trials, clicks were presented at a rate of 100/s to a true rms voltmeter (Fluke 8920A) and set to produce 60 dB SPL through STAX SR5 electrostatic earphones. There is really no good way to characterize the strength of single clicks in terms commonly used in psychoacoustics, and that is why rms levels were measured with continuous trains. The most accurate physical description of a single transient is in units of energy, and we have suggested that the reader should be given sufficient information to calculate energy if so desired (Buell and Hafter, 1988). For this, one must know the equivalent rectangular duration (ERD) of the squared waveform (sound power) and the average power. For a Gaussian, the ERD is $\pi\sigma$. In the present experiment, the ERD was 0.403 ms and the rms level of the 4000-Hz sinusoid before multiplication by the Gaussian window was 74 dB SPL.

Discrimination was measured using a two-interval forced-choice task, with the IDT leading to the right ear in one interval and to the left in the other. Listeners were told to expect a signal that would move laterally between the two intervals and to indicate the direction of movement by pressing the appropriate button. The intervals were separated by 300 ms, and 1700 ms was allowed for response. Immediate visual feedback signaled the correct response. Before each set of 50 trials, subjects were presented with a continuous train of diotic clicks (100/s) and instructed to adjust the position of the headset so as to center the auditory image. Subjects were students at the University of California, including one of the authors. None was known to have a hearing loss.

Trains consisted of either 1, 6, 12, 24, or 48 clicks. The ICI was 2.5 ms. Gaps, where present, were either 5 or 7.5 ms, breaking the trains into halves or quarters.

C. Results and discussion

Figure 4 shows the data for each of the six subjects. The ordinates are plotted in units of relative threshold, that is, the threshold for each condition divided by the threshold for a single click.[1] As in the hypothetical drawing in Fig. 3, solid squares show the results for unbroken trains and the solid lines through them are least-squares best-fitting straight lines forced through a Y intercept of 1.0. All of the dotted lines have slopes of -0.5. That is to say, each is a theoretical prediction for the case of independent coding of segments separated by gaps as described in the discussion of Fig. 3. The triangles represent thresholds for gaps of 5 ms (open) and 7.5 ms (closed), respectively. As predicted, the results show recovery from adaptation, with the thresholds for sets of two or four clusters, respectively, approaching $1/\sqrt{2}$ or 1/2 times the thresholds for the appropriate single cluster.

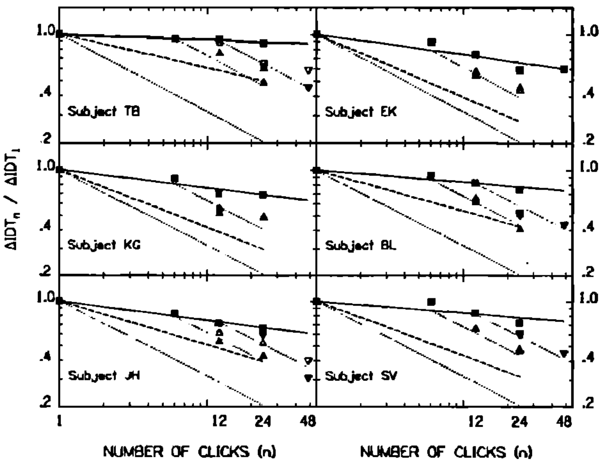

FIG. 4. Results with trains interrupted by gaps; data are shown separately for individual subjects. Solid squares represent trains with ICIs of 2.5 ms and no gaps; they are fitted with the solid lines forced through the threshold for one click. Results with clusters of six clicks and a gap of 5 ms are represented by △; six clicks and 7.5 ms by ▲; 12 clicks and 5 ms by ▽; 12 clicks and 7.5 ms by ▼. Dotted lines have slopes of -0.5. The long-dashed line was fitted to results with uniform trains, i.e., no gaps, and an ICI of 7.5 ms.

Figure 5 helps us to see the magnitude of the effect by showing the relation between thresholds found with short trains and long, both with and without gaps. Data from each subject are plotted separately. In the left half of the drawing,

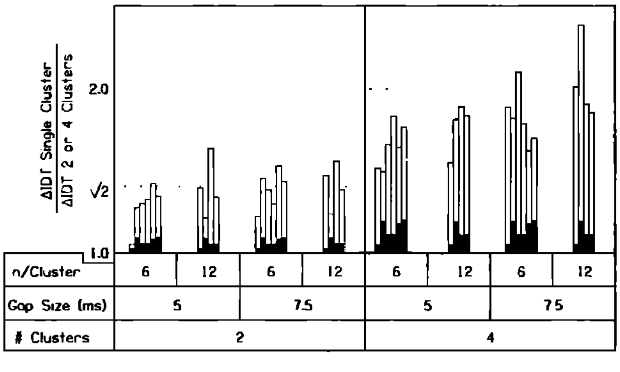

FIG. 5. Relative thresholds in response to a doubling or quadrupling of *n*. Individual bars represent individual subjects. Filled bars depict conditions with no gaps, open bars with gaps. Thus the leftmost group of filled bars shows ratios of the fitted thresholds for a train of six clicks to the obtained thresholds found with 12 clicks. The comparable open bars show the ratio of the thresholds obtained with a train of six clicks to the thresholds found with a train composed of two clusters of six clicks separated by a gap of 5 ms.

the height of each bar shows the ratio between the threshold found with an unbroken train of 6 clicks or 12 clicks and that found with a train of twice the length. The baseline value of 1.0 would be expected if no information were added by the second half of the train. The bars are ratios of thresholds. Their numerators are the fitted values taken from the solid lines in Fig. 4. For the filled bars representing cases with no gaps, the denominators are also fitted values taken from Fig. 4. The open bars show results for conditions with gaps. Here, the denominators of the ratios are the thresholds obtained with the trains broken into two clusters. Thus, for example, the leftmost group of bars compares the thresholds obtained with 6 clicks and 12, with the open bars being the case in which the 12 were broken into two sets of 6 by a gap of 5 ms. The dotted line at 2 shows what would be achieved if the second cluster were as effective as the first. In the right half of the figure, the trains represented in the denominators were four times as long as those in the numerators. Gaps, where present, broke the trains into four equal parts; thus the dotted line shows what would be found if the last three clusters were as effective as the first is at 4.

The shallow slopes of the fitted lines in Fig. 4 show up in the filled bars of Fig. 5 as ratios just greater than 1.0. Clearly, the 2.5-ms ICI produced strong adaptation. Just as clearly, the closeness of the open bars in the left half of the figure to the predicted value of 2 shows that with the exception of the leftmost subject (TB) for an ICI of 5 ms, virtually complete recovery could be provoked by single gaps of either 5 or 7.5 ms. Results in the right half of the figure are less conclusive. While performance clearly improved with the introduction of three gaps, it rarely reached the predicted factor of 2.0. From these data one is tempted to propose additional limitations on the efficacy of multiple restarts; however, there is insufficient evidence to support such a claim though it poses an interesting hypothesis for examination in future experiments.

II. EXPERIMENT 2: TRIGGERED WITH BURSTS OF NOISE OR TONE

A. Rationale

A surprising result from experiment 1 was the discovery that binaural processing was restarted by gaps as short as 5 ms. Our surprise was based not so much on a preconceived notion of how long the time constant of adaptation ought to be as much as it was on the results from the condition illustrated by the lower panel in Fig. 6. Here, the 7.5-ms spacing used as a gap in trains with an ICI of 2.5 ms was itself the ICI in trains having no gaps. Lines fitted to those data are shown by the long dashes in Fig. 4. For every subject, the slopes of the lines are shallower than -0.5. Thus, while 7.5 ms provoked recovery from adaptation when embedded in a train with a 2.5-ms ICI, it produced adaptation when the rate was uniform. From this, we concluded that the gaps had not merely acted as quiet periods during which adaptation could dissipate, but rather served as *active triggers* that *restarted* sampling of the interaural information.

The idea of active triggering led to speculation about what feature of the gap might have provided restarting. One possibility was that transient changes in the amplitude/phase spectrum, introduced by the gaps, could have triggered the restart. Experiment 2 was intended to see if restarting would occur in response to the introduction of other changes in the spectrum.

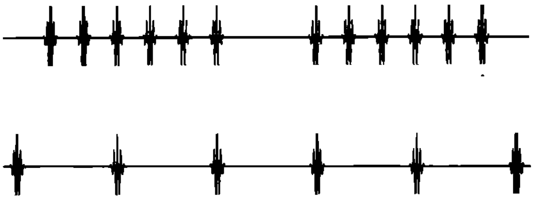

FIG. 6. A condition designed to examine the reason for the effectiveness of the gap in provoking a restart. The upper trace shows a train of six clicks with an ICI of 2.5 ms and a gap of 7.5 ms. The lower trace shows a uniform train with an ICI of 7.5 ms; it describes the condition used to produce the results described by long-dashed lines in Fig. 4.

B. Procedure

Uniform trains, like those used for control in experiment 1, were employed with the exception that additional brief sounds were superimposed on the train during the course of adaptation. Potential triggers were 5-ms bursts of either wideband noise or tone, gated on and off without ramps. These were placed at the midpoints of a train. The noise, generated in the computer by sampling voltages at random from a uniform distribution, was filtered only by the 20-kHz anti-imaging filters and the STAX headphones. Bursts of noise were presented either diotically, interaurally uncorrelated, or monaurally. The ungated rms level of the noise was either "low," 44 dB SPL, or "high," 50 dB SPL. Diotic tonal triggers were sinusoids of either 1, 2, 3, or 4 kHz, switched on in sine phase without ramps. Their levels were 40 dB SPL. With durations of only 5 ms, the triggers were audible but very quiet. Again, the hypothesis was that recovery from adaptation would be seen if the trigger divided the trains into equally effective clusters.

C. Results and discussion

Figures 7 and 8 show the results from four listeners for conditions in which the potentially active trigger was a burst

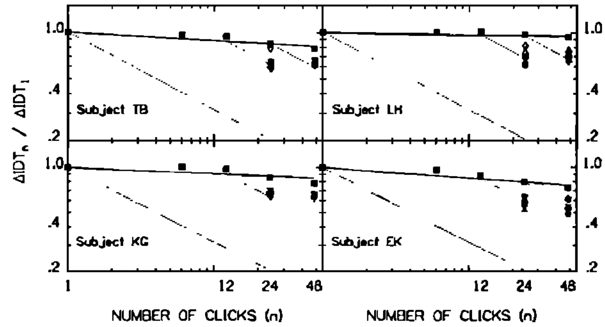

FIG. 7. Results with 5-ms bursts of noise used to trigger restarting; data are shown separately for individual subjects. Solid squares represent trains with ICIs of 2.5 ms and no noise bursts; they are fitted with the solid lines forced through the threshold for one click. Dotted lines have slopes of -0.5. The various types of noise were: diotic, low-level, ▼; diotic, high-level, ▲; monaural, low-level, ◆; monaural, level noise ⧗; interaurally uncorrelated, low-level, +; and uncorrelated, high-level *.

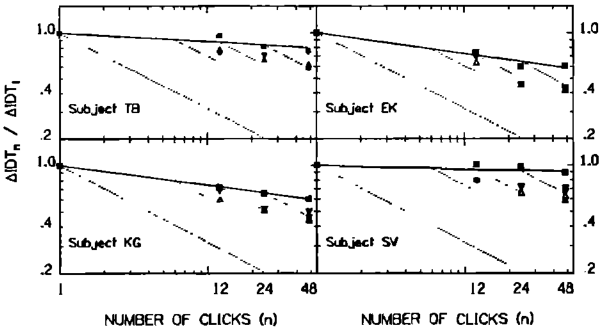

FIG. 8. Results with 5-ms bursts of tone used to trigger restarting; data are shown separately for individual subjects. Solid squares represent trains with ICIs of 2.5 ms and no tone bursts; they are fitted with the solid lines forced through the threshold for one click. Frequencies of the tones were: 1000 Hz, △; 2000 Hz, ▲; 3000 Hz, ▽; 4000 Hz, ▼.

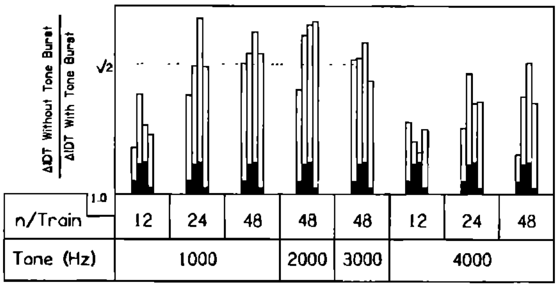

FIG. 10. Relative changes in thresholds in response to a 5-ms burst of tone centered on the train. Individual bars represent individual subjects. Filled bars depict conditions with no tone, open bars with tones. Thus the filled bars in the leftmost group show the ratios of thresholds obtained with a train of six clicks to the thresholds found with 12 clicks. The comparable open bars show the results when a burst of 1000-Hz tone was present.

of noise or a tone. In principle, one might be able to determine the precise instant when restarting occurred, for example, at the beginning of the 5-ms tone burst or at its end; but in practice, the differences in prediction are small relative to normal variation in psychophysical tests and are probably unmeasurable. As shown with gaps in Fig. 4, acoustic triggers were able to provoke recovery from adaptation.

Figures 9 and 10 are similar to Fig. 5, plotting the ratios of predicted performance, with and without triggers. They show that bursts of noise were generally more effective at provoking a restart than tones, though results with the latter are complicated because of the relative ineffectiveness of tones at 4000 Hz. The latter might be attributed to partial masking of the tone bursts by the clicks themselves, but that would not explain why the effects were also less for 1000 Hz and 12 clicks. Regardless, in even the least effective cases, performance was better with all of the acoustic triggers than with none at all.

One could argue that the effectiveness of a diotic burst of tone or noise derives not so much from a restarting of binaural processing as from a perceptual cueing, with the burst marking the midline position around which the lateralized images in the forced choice are heard. That is why testing was done with interaurally uncorrelated and monaural noise as well as with the diotic noise. The fact that there were no discernible differences between these conditions supports the argument that improvements were based on a true recovery from adaptation.

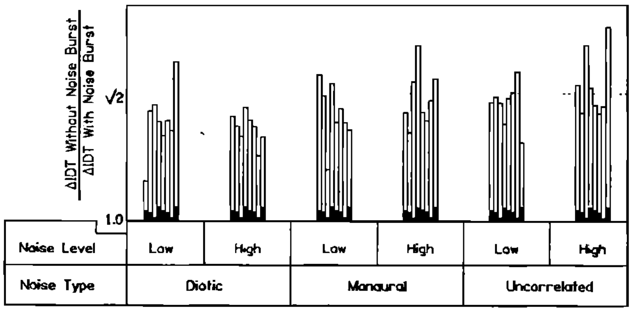

FIG. 9. Relative thresholds in response to a 5-ms burst of noise centered on the train. Individual bars represent individual subjects. Filled bars depict conditions with no noise, open bars with noise. Thus the first four filled bars in the leftmost group show ratios of the fitted thresholds for a train of 12 clicks to the obtained thresholds found with 24 clicks; the second four show ratios of the fitted thresholds for a train of 24 clicks to the obtained thresholds found with 48 clicks. The comparable open bars show the results when a burst of low-level, diotic noise was presented.

While the paradigms are quite different, the results here are reminiscent of another experiment (Hafter *et al.*, 1979) in which an attempt was made to study lateralization of signals without onsets (SWOON). In SWOON conditions, listeners heard only a continuous masking noise except during the durations of the two observation intervals. At the beginning of each interval, the noise was gradually turned off, leaving a continuous tone to be lateralized; at the end of the interval, the masker smoothly returned, once again masking the signal. Performance with SWOON was roughly the same as in control conditions (with gated sinusoids and no flanking masker) as long as the signals in SWOON were made longer than those in the control conditions, presumably offsetting reductions in the effective durations of the signals due to forward and backward masking by the noise. In that paper, the ability to lateralize in the absence of "onsets" was seen as evidence of lateralization based on ongoing interaural cues but, in light of the present results, one might argue instead that changes in the spectrum produced by turning off the masker may have triggered renewed sampling.

III. EXPERIMENT 3: A CONDITION IN WHICH RESTARTING DID NOT OCCUR

A. Rationale

It would appear that the primary conclusion that one might draw from the results with bursts of noise and tone is that binaural adaptation is an *active* process, rapidly undone by any change in the acoustic pattern. The notion seems well supported by the results from a brief demonstration in which recovery from adaptation during a train with an ICI of 5 ms was produced by the introduction of a "squeeze," i.e., an ICI of 2.5 ms in the center of the train. However, one final attempt to induce recovery produced results quite different from the rest. Here, we would attempt to trigger a restart with only the disappearance of a competing signal.

B. Procedure

In this case, the prospective trigger was again a 1000-Hz tone but here it was not a brief burst. Rather, a tone of relatively long duration came on either at the beginning of the train and remained on until the midpoint when it was turned off, or at the midpoint and stayed on throughout the remainder of the train. Gating of these long duration tones was done at an axis crossing and, for various conditions, the tones were either diotic, monotic, or interaurally reversed in phase. For comparison with a similar stimulus with no trigger, one condition used a tone that was on throughout the entire train.

C. Results and discussion

If the only criterion for recovery from adaptation were that there be a discernible change in the spectrum, one might expect that the tone turned either off or on at the center of the train would produce restarting. Figure 11 shows that this was not the case. Here, there was no improvement; rather, performance with a tone was, if anything, worse than that with no tone at all. Given the other results, this is perplexing. However, a possible explanation comes from McFadden and Pasanen (1976), who found conditions in which lateralization in one region of the spectrum was diminished by presentation of a diotic stimulus in another region and from Trahiotis and Bernstein's (1986) demonstration that perceived lateral displacements based on IDTs seem dominated by the lower frequencies in the stimulus. Perhaps the long 1000-Hz tones in the present experiment simply overshadowed the interaural cues in the higher-frequency train of clicks. It would be interesting to pursue this condition with frequencies higher than those in the signals and with more extensive practice. Regardless, these data show that it cannot be argued that restarting is a universal response to spectral change.

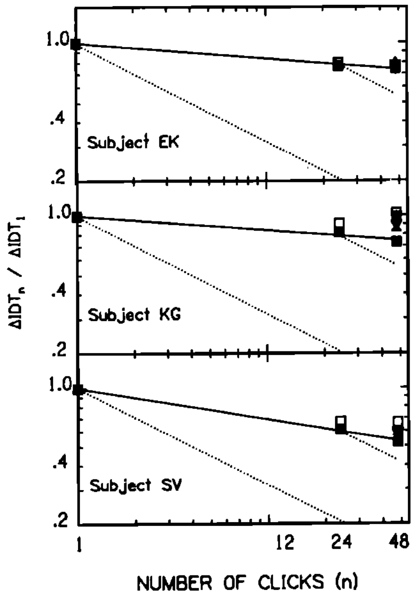

FIG. 11. The effects of continuous 1000-Hz tones with durations equal to half or all of the train; data are shown separately for individual subjects. Solid squares represent trains with ICIs of 2.5 ms and no tone bursts; they are fitted with the solid lines forced through the threshold for one click. Various conditions include a diotic tone: on continuously throughout the train, □; a diotic tone on throughout the first half of the train, ▲; a diotic tone on throughout the second half of the train, ▼; a monaural tone on throughout the second half of the train, ▽; an interaurally reversed tone on throughout the second half of the train, ⧗.

IV. GENERAL CONCLUSIONS

Leaving out, for the moment, the results with tones of long duration, the data suggest that resampling of binaural information typically occurs in response to a change in the acoustic environment. This, of course, begs the question, "What is a change?" Clearly, each successive click in a uniform train is a change from the silent ICI but this does not prevent adaptation. One possibility is that fluctuation alone is not enough and that, in order to be effective, the change must violate some *expectation*, possibly signaling the onset of a *new* stimulus in the environment. This does not mean to say that the process must be cognitive in the sense of a higher-order process that *recognizes* the meanings of sounds. The sign of a new stimulus might be nothing more than the appearance of energy in a heretofore quiescent band, and the rapidity of restarting suggests that the recognition of and response to change occur early in the auditory system. This idea is consistent with results from experiments designed to determine the neural site of binaural adaptation by measuring its interaction with other auditory functions (Hafter and Wenzel, 1983; Hafter and Buell, 1985; Hafter *et al.*, 1988); they all suggest that the adaptation occurs prior to binaural interaction. Clearly, more experiments with different kinds of triggers and maskers are needed.

In discussing the functional value of binaural adaptation, Hafter *et al.* (1988) suggest that the accuracy of onset-coded localization may be sufficient for survival. They argue that reliance on sensory memory to keep track of unchanging objects could reduce the load on central auditory processing. Indeed, one wonders if other information used by the central auditory system shows similar adaptation. With this in mind, Hafter and Richards (1988) showed that this is not the case for periodicity pitch. Asking subjects to discriminate between trains of clicks with ICIs of either ICI ms or ICI–ΔICI ms, they found *n* improvements in thresholds for trains as long as 64 clicks, even with very short ICIs. Thus it seems that, for perception of pitch, perhaps identifying *who* or *what* made the signal, there is effective use of ongoing information; but for computing location, that is, the *where* of the signal, there is reliance on a sample-on-demand process that extracts the interaural cues only when there is a new signal.

V. SUMMARY

(1) The ability to detect interaural differences of time (Hafter and Dye, 1983) or intensity (Hafter *et al.*, 1983) in a train of high-frequency clicks with short ICIs is limited by a form of adaptation that renders each click in the train less effective than the one preceding it. Numerous studies have shown that this binaural adaptation (Hafter *et al.*, 1988) is rate-dependent, ranging from no effect with click rates as low as 85–100/s (ICI = 10 to 12 ms) to complete post-onset adaptation with rates above about 500/s (ICI = 2 ms) (Buell and Hafter, 1988).

(2) Of special interest here is the recovery from binaural adaptation, and more specifically the conditions necessary to induce the auditory system to resample interaural information. The logic of the experiments argues that, where there is adaptation in the response to a train of 24 clicks, recovery at the midpoint is indicated if the information extracted from the second cluster of 12 clicks is the same as that from the first.

(3) Experiment 1 showed that gaps as small as 5 ms inserted into trains with ICIs of 2.5 ms could provoke complete recovery. However, it was also shown that trains with no gaps but with ICIs of 7.5 ms led to adaptation, indicating that the period of nonstimulation *per se* was not the critical factor.

(4) Based on the idea that spectral change introduced by the gap had provoked recovery, experiment 2 was designed to see if other signals could serve as active triggers that would restart binaural processing. Short bursts of diotic, monaural, and interaurally uncorrelated noise, as well as tone bursts of 1000, 2000, 3000, and 4000 Hz, were shown to be effective triggers for restarting. Furthermore, in one condition, a gap smaller than the ICI (2.5-ms gap, 5-ms ICI) successfully triggered a restart. We should note that, while changes in the stimulus train designed to provoke restarting always produced an improvement in lateralization, the magnitude of the improvement was sometimes less than as predicted. It is unclear whether this was due to less-than-complete recovery or was simply the result of including in the averages some trials in which there was no recovery at all.

(5) Failure to trigger a restart occurred when a 1000-Hz tone was turned on at the beginning of the train and off at its midpoint or was turned on at the midpoint and left on until the end. A possible explanation is that the 1000-Hz signal interfered with the lateralization of higher frequencies.

(6) In summary, the binaural auditory system adapts when presented with information at too high a rate. With the exception of the case with the long duration tone, all of the results indicate that recovery from adaptation is provoked by a variety of acoustic triggers. This is interpreted as showing that processing of rapidly presented interaural information is governed by a sample-on-demand process, whereby the binaural system utilizes successively less information unless there is a change in the stimulus.

---

[1] The individual values of the thresholds for single clicks produced by each subject were: (subject) TB, 42 μs; BL, 92 μs; JH, 223 μs; SV, 72 μs, EK, 34 μs; KG1, 73 μs; KG2, 84 μs; LH, 75 μs.

Buell, T. N., and Hafter, E. R. (**1988**). "Discrimination of interaural differences of time in the envelopes of high-frequency signals: Integration times," J. Acoust. Soc. Am. **84**, 2063–2066.

Hafter, E. R., and Buell, T. N. (**1985**). "The importance of transients for maintaining the separation of signals in auditory space," in *Attention and Performance XI*, edited by M. Posner and O. Marin (Erlbaum, NJ).

Hafter, E. R., Buell, T. N., and Richards, V. M. (**1988**). "Onset-coding in lateralization: Its form, site and function," in *Auditory Function: Neurobiological Bases of Hearing*, edited by G. M. Edleman, W. E. Gall, and W. M. Cowan (Wiley, New York).

Hafter, E. R., Dye, R. H., Jr., and Gilkey, R. H. (**1979**). "Lateralization of tonal signals which have neither onsets nor offsets," J. Acoust. Soc. Am. **65**, 471–477.

Hafter, E. R., and Dye, R. H., Jr. (**1983**). "Detection of interaural differences of time in trains of high-frequency clicks as a function of interclick interval and number," J. Acoust. Soc. Am. **73**, 644–651.

Hafter, E. R., Dye, R. H., Jr., and Wenzel, E. (**1983**). "Detection of interaural differences of intensity in trains of high-frequency clicks as a function of interclick interval and number," J. Acoust. Soc. Am. **73**, 1708–1713.

Hafter, E. R., and Richards, V. M. (**1988**). "Discrimination of rate in filtered pulses," Percept. Psychophys. **43**, 405–414.

Hafter, E. R., and Wenzel, E. M. (**1983**). "Lateralization of transients presented at high rates: Site of the saturation effect" in *Hearing: Physiological Bases and Psychophysics*, edited by R. Klinke and R. Hartmann (Springer-Verlag, Berlin).

McFadden D., and Pasanen, E. G. (**1976**). "Lateralization at high frequencies based on interaural time differences," J. Acoust. Soc. Am. **59**, 634–639.

Nuetzel, J. M., and Hafter, E. R. (**1981**). "Discrimination of interaural delays in complex waveforms: Spectral effects," J. Acoust. Soc. Am. **69**, 1112–1118.

Trahiotis, C., and Bernstein, L. R. (**1986**). "Lateralization of bands of noise and sinusoidally amplitude-modulated tones: Effects of spectral locus and bandwidth," J. Acoust. Soc. Am. **79**, 1950–1957.