Discrimination of the rate of filtered impulses

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When subjects detect changes in interaural differences of time or level in the envelope of a complex waveform, the accuracy of the detection depends on the stimulus's duration. The change in threshold with duration, in turn, depends on the rate of modulation of the waveform's envelope. As the envelope rate increases beyond about 85 Hz, detectability relies increasingly on information derived from the early portion of the signal. The purpose of the present experiment was to determine whether a similar reliance on onset information might affect the detection of changes in envelope rate per se. The stimuli were trains of high-frequency, filtered clicks that differed only in their click rates. Control conditions included low-frequency noise intended to interfere with nonlinear distortion and a roving carrier technique designed to discourage comparisons between individual harmonic components. Unlike the case for lateralization, rate-discrimination thresholds for click rates as high as 400 Hz declined with the square root of duration, indicating that listeners derived information from throughout the stimulus. From these data it is suggested that separate channels may be used to convey envelope information for spatial hearing and for the discrimination of pitch.

It has long been known that trains of impulses repeated at moderate rates produce a pitch associated with the click rate; the connection between this pitch and the period of the signal has given rise to the name *periodicity pitch*. The spectrum of such signals concentrates energy at frequencies harmonically related to the fundamental frequency (inverse of the period), and much of the interest in them has stemmed from the fact that their pitch remains strong even when the fundamental itself is absent. This result has led to models that suggest that the listener uses some form of correlational analysis to extract periodicity in either the time (e.g., Schouten, 1940, 1970; Schouten, Ritsma, & Cardozo, 1962) or the frequency (e.g., Goldstein, 1973; Terhardt, 1974; Wightman, 1973) domain.

The present study was designed to examine one aspect of periodicity coding, the effect of signal duration on the ability to discriminate between two complex signals of different fundamental frequencies. It was motivated by the results of a series of experiments on lateralization, in which the ability to derive information from the envelopes of high-frequency complexes was studied by measuring the detectability of interaural differences of time or intensity in trains of high-frequency clicks. In such cases, the effectiveness of the interaural information tends to be nonuniform over the duration of the train, declining after the stimulus's onset. The intent here was to apply a similar analysis to the discrimination of click rate, that is, the discrimination of periodicity pitch, to determine the course of information accumulation from a complex signal where binaural interaction is not involved.

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Analysis of the Useful Information in a Train of Clicks

In the most common of the binaural experiments, subjects have listened for interaural differences of time (IDTs) in trains of high-frequency (bandpassed at 4 kHz) clicks (Hafter & Dye, 1983). Click rate was denoted by its inverse, the interclick interval (ICI), duration by the number of clicks in a train (n), and threshold (ΔIDT_n) by the interaural delay necessary to produce a d' of 1.0. One must assume that discrimination in such experiments is limited by an "internal noise" in the domain of the signal, here a temporal jitter added by the nervous system of the observer. Detection theory argues that the standard deviation of the internal noise can be obtained directly from the threshold for a single dichotic click ($n=1$) since

$$d' = 1.0 = \frac{\Delta\text{IDT}_1}{\delta_{\text{IDT}_1}} \quad (1)$$

Where the train consists of more than one click, if each is equally effective and if the jitter added to the successive samples of the IDT is independent, statistical averaging across the sum of the IDT + jitter should lead to a $\sqrt{n}$ improvement in performance:

$$\Delta\text{IDT}_n = \frac{\Delta\text{IDT}_1}{n^{0.5}} \quad (2)$$

For comparisons to data, we have found it useful to use the logarithmic form of this expression, which predicts a straight line with intercept at the log threshold for a single click and slope of -0.5 :

$$\log \Delta\text{IDT}_n = \log \Delta\text{IDT}_1 - 0.5 \log n \quad (3)$$

Lateralization and the Effects of Click Rate

Whereas listeners readily detect IDTs in single transients regardless of frequency content, they cannot do so

if the signal is an ongoing high-frequency tone (Blauert, 1983) or an amplitude-modulated high-frequency tone with a high rate of modulation (Nuetzel & Hafter, 1981). This implies that for interaural delay, the initial transient is more informative than the portion that follows. In pursuit of this notion, Hafter and Dye (1983) suggested the use of a "method of subtraction" (Hafter, Buell, & Richards, in press), whereby differences found between thresholds obtained with two different stimulus durations are attributed to information carried in the extra portion of the longer signal. For these tests, they used click trains of various lengths (n) and examined the effect of increasing the rate ($1/ICI$). To describe the actual effectiveness of successive clicks, they rewrote Equation 3 in terms of an intervening variable, N_n , defined as the number of informative neural events evoked by a train of length n :

$$\log \Delta IDT_n = \log \Delta IDT_1 - 0.5 \log N_n. \quad (4)$$

Clearly, psychophysics alone cannot substitute for the direct observation of neural activity, but it allows for relative measures through which the effectiveness of one stimulus can be compared with that of another. While Equation 3 expresses a theoretical relation that holds only for the special case in which each click is equally effective, there is no such constraint on the empirical relation described by Equation 4, which deals with the actual effect of the train. Comparison between the optimal and the obtained functions produces the relation between N_n and n , which, when combined with the "method of subtraction," shows the relative effectiveness of each click in producing the detection. From the joint relation, $N_n = f(n, ICI)$, one may determine the extent to which the relatively poor performance observed at high rates is due to a lack of information transduced after the initial transient.

Nonlinearity in the Binaural Response to High Rates

One can imagine a variety of neural processes that might curtail the use of information derived from trains with high rates. Hafter and Dye (1983) showed that many of these processes affect the relations described by Equation 4 in essentially the same way. This group includes (1) neural refractoriness, which make it possible for a click to occur during the refractory periods of individual units; (2) the restriction of bandwidth imposed by the auditory filters, which reduces the depth of modulation and thus increases variance in the transduction from mechanical to neural activity; and (3) any lack of independence between successive samples of the added internal noise. Although each of these processes is information-destructive, albeit for different reasons, they all predict that the result of higher click rates should be to reduce performance in such a way that the terminal slope of the log threshold, $\log n$ functions remain a constant -0.5 . Because a slope of -0.5 means that N_n is proportional to n , the effects of the three limiting processes are said to be stationary; that is, they act uniformly throughout the duration of the train.

The most interesting fact to come out of the experiments on lateralization has been that stationarity does not hold for higher click rates. Numerous experiments (Buell & Hafter, 1986; Dye & Hafter, 1984; Hafter & Buell, 1985; Hafter & Dye, 1983; Hafter, Dye, & Wenzel, 1984) have shown that for fairly low rates (ICIs on the order of 10 to 12 msec), the slopes of the log-log functions are indeed 0.5. However, this is not the case for higher rates, where the data are better fit by the expression

$$\log \Delta IDT_n = \log \Delta IDT_1 - 0.5 k \log n, \quad (5)$$

where $0 \leq k \leq 1$ and $k = f(ICI)$. Equation 5 captures the experimental fact that the slopes grow more shallow with increased rate, the limiting case of 0.0 having been observed for ICIs on the order of 2 msec. The change in slope shows that, rather than the usually considered limitations on high stimulus rates (1 through 3 above), there is a process whose action is nonuniform over the duration of the stimulus. By applying the logic of Equation 4 to the inverse logarithm of Equation 5,

$$\Delta IDT_n = \frac{\Delta IDT_1}{n^{(k)(0.5)}}, \quad (6)$$

we find that the relation between numbers of clicks and evoked neural responses is a compressive power function,

$$N_n \propto n^k, \quad (7)$$

where $0 \leq k \leq 1$. Values of k less than 1.0 indicate that each click in the train evoked fewer responses than the one that preceded it.

The hypothetical results shown in Figure 1 illustrate this interpretation for conditions distinguished by ICIs that range from relatively long at the top to relatively short at the bottom. The first column plots log thresholds against $\log n$ for k s of 1.0, 0.7, and 0.2, and so slopes of -0.5 , -0.35 , -0.1 , respectively. The second column shows the relation between N_n and n implied by Equation 7. The vertical bars of the third column represent the derivatives of the functions in column 2 at discrete values of n . These represent the relative effectiveness of each click in the train. Note that for the stationary case, $k = 1$, all clicks are equally effective, whereas for $k = .2$, virtually no information is transduced beyond the first. In earlier papers, we referred to this as "post-onset saturation"; however, because saturation has multiple meanings, we have adopted the name "binaural adaptation" (Hafter et al., in press). A review of much of the research on binaural adaptation can be found in Hafter and Buell (1985).

Are There Rate-Dependent Changes in the Discrimination of Periodicity?

Hafter and his colleagues (Hafter, 1983; Hafter & Buell, 1985; Hafter et al., in press; Hafter & Wenzel, 1987) have provided evidence to suggest that the neural locus of "binaural adaptation" is at a level in the auditory system peripheral to binaural interaction, in what are essentially monaural channels. Thus, it was natural to examine the

Figure 1. Hypothetical lateralization results and interpretation. The first column presents hypothetical lateralization data (based on Hafer & Dye, 1983) as the interclick interval (ICI) is reduced (top to bottom). Thresholds for interaural differences in time (Δ IDT) are plotted as a function of the number of clicks in the train (n). As the click rate is increased, the slope of the function relating $\log \Delta$ IDT and $\log n$ is reduced. The second column presents the implied relationship between the hypothetical variable N , and the number of clicks in the train. k s of 1.0, 0.7, and 0.2 were used. The third column presents the effectiveness of each click in the train. For long ICIs, each click is equally informative; for short ICIs, little information is transduced beyond the first click.

joint effects of envelope rate and duration in a monaural task, namely, frequency discrimination. The stimuli were similar to those used in the binaural experiments, except that the cues to be detected were changes in the click rate (CR). Following the logic described above, one may assume that the task is limited by an internal noise (temporal jitter) added to each of the $(n-1)$ periods in the click train. Calling the number of periods m , then, for trains of lengths m_i and m_j , the situation in which each period is equally effective provides the relationship

$$\Delta CR_{m_j} = \frac{\Delta CR_{m_i}}{\{m_j/m_i\}^{0.5}}. \quad (8)$$

Similarly, its logarithmic form is a straight line with a slope of -0.5 :

$$\log(\Delta CR_{m_j}) = \log(\Delta CR_{m_i}) - 0.5 \log\{m_j/m_i\}. \quad (9)$$

Since the point of the experiment was to examine the relative effectiveness of each period, we have again resorted to a hypothetical intervening variable, M_m , here defined as the number of neural representations of the m periods. As before, the efficacy of successive portions of the envelope would be defined by the relation between

M_m and m , found by comparison of data with the hypothetical function

$$\log(\Delta CR_{m_j}) = \log(\Delta CR_{m_i}) - 0.5 \log\{M_{m_j}/M_{m_i}\}. \quad (10)$$

METHOD

In a two-interval, forced-choice (2IFC) procedure, listeners compared diotic trains whose CRs were $1/ICI$ and $1/(ICI + \Delta ICI)$ Hz, respectively. Although their spectra consisted of predominantly higher harmonics, these trains have a distinct pitch, similar to those of tones whose frequencies equal the corresponding fundamentals.

Spectra

Figure 2 describes the stimulus, in both the time and frequency domains. Figure 2a shows the building block for a train, a single click. It was produced by multiplying a Gaussian envelope by a sinusoid, the center frequency (f_{cen}), which was set to cosine phase at the center of the envelope. The amplitude spectrum of such a click is continuous and Gaussian, and centered at f_{cen} . Figure 2b depicts a hypothetical train whose CR is 250 Hz but whose length is infinite. It has a line spectrum with components only at harmonics of the fundamental frequency. The amplitudes of the components are weighted by the same Gaussian spectrum as that of a single click. Figure 2c shows the result of fixing the length of the train. Here,

Figure 2. Time and frequency representation of the signal. The top panel (a) shows a single Gaussian click (center frequency of 3500 Hz). The middle panel (b) presents a hypothetical, infinitely long click train, with a 4-msec ICI (250-Hz click rate). The bottom panel (c) presents a train of four clicks.

energy is spread into regions between the harmonic frequencies according to the convolution of the line spectrum of Figure 2b and a *sinc* function, $\sin(\pi \cdot f \cdot D)/\pi \cdot f \cdot D$, where the duration (D) consists of m periods plus the width of the terminating click.

Center Frequencies and Bandwidths

Two different bandwidths, determined by the durations of the individual clicks, were tested. How one describes the duration of a Gaussian impulse is somewhat arbitrary; we used the standard deviation of the Gaussian envelope. Similarly, bandwidth is described by the distance in the amplitude spectrum between components at $f_{cen} \pm \sigma_f$ Hz. Table 1 presents parameters of clicks in the nominally narrow- and wideband conditions.

Signals were created with a PDP-11 computer using a sampling rate of 50 kHz. The digital signals were then transformed via a 14-bit digital-to-analog converter with deglitching and passed through a 48-dB/octave analog filter (Frequency Devices 901F) set to 10 kHz. The signal level was set such that a train of clicks presented at 100 clicks/sec had an RMS sound pressure level of 60 dB SPL. Given normal listening abilities, only the central portion of the spectrum and the two or three lobes on either side of it were assumed to be audible in the narrow-band conditions; the wideband conditions offered an increased number of potentially audible components but at the expense of reducing the absolute levels of common components.

For most of the conditions tested, the center frequency was 3500 Hz (see below for a discussion of cases in which the center frequency was varied within a trial). The values of CR ranged from

150 to 400 clicks/sec. Over the course of the experiment, the lengths of trains ranged from 8 to 64 clicks.

The Roving Center Frequency

Although all of our subjects claimed to hear the fundamental pitches (later confirmed by pitch matching with an oscillator), and to base their responses on them, we thought it necessary to consider the possibility that the listener might treat the experiment as a problem in amplitude discrimination, monitoring the levels in an auditory filter at the frequency of one of the components and saying "low pitch" or "high," depending on those levels (Henning, 1967). Although some investigators (e.g., Viemeister & Burns, 1976) have attacked this problem by generating periodicity with modulated noise, with pitch generated from repeated pulses, another solution was needed. For this reason, a subset of the experiment was repeated, using a roving center frequency. In these cases, f_{cen} for each interval of the 2IFC was chosen at random from a list ranging uniformly from 3000 to 3500 Hz. Thus, within any given auditory filter, the interval containing the higher level could come from either the lower or higher click rate. As shown in Figure 2, the individual components were always a harmonic sequence of the CR, regardless of the center frequency of the Gaussian filter. Thus, roving f_{cen} affected only the relative amplitudes of the sequence.

Two CRs, 250 and 167 Hz, and four train lengths (m), 7, 15, 31, and 63, were tested. Thresholds for these conditions were completed using both roving and fixed center frequencies.

Lowpass Noise

When studying the presumed effectiveness of the envelope of a complex signal, one must worry about potential confounds introduced by nonlinear distortion in either the apparatus or the auditory systems of the listeners. To check for this possibility, a subset of the conditions were tested both in the quiet and in the presence of a lowpass noise. When present, continuous noise was shaped by two Krohn-Hite filters (3500R and 3100) placed in tandem; together, these produced an attenuation on the lowpass skirt of 48 dB/octave. The 3-dB downpoint was at approximately 2000 Hz. The spectral density of the lowpass noise was 0 dB SPL.

Thresholds were determined both with and without lowpass noise for CRs of 150, 250, and 400 Hz. The durations of the trains, in units of m , ranged from 7 to 47.

Table 1
Durations and Bandwidths for the Two Types of Clicks

Click Type	Duration (msec)	Bandwidth (Hz)
Narrow band	0.45	700
Wideband	0.28	1120

Note—Clicks were made by multiplying a Gaussian weighting function by a cosine. Duration here refers to the standard deviation of the Gaussian envelope. The amplitude spectrum of such trains of clicks is also Gaussian, and the bandwidths given here refer to frequencies included between $\pm 1\sigma$ points.

Figure 3. Thresholds for changes in click rate ($\Delta\text{CR}/\text{CR}$) as a function of the number of periods in the click train (m). Both are plotted logarithmically. The top panel presents data for a CR of 167 Hz (triangles), the bottom panel a CR of 250 Hz (circles). Filled symbols indicate that the center frequency was roved (3000-3500 Hz); open symbols indicate a fixed center frequency (3500 Hz). The dashed lines have a slope of -0.5 . Data for 3 subjects are presented.

Procedure

Within the 2IFC, each trial consisted of the two intervals to be discriminated, separated by 300 msec, plus approximately 2 sec for a response. The subjects used buttons to indicate which of the two pitches was higher, and they received immediate visual feedback. Percentages of correct responses were computed for runs of 50 trials and used to draw psychometric functions based on at least eight runs per function. The interpolated point for 76% correct served to define thresholds (Elliot, 1964). Each subject had at least 40 h of experience at discriminating pitches in complex signals before data collection began. In general, the data for a given CR were gathered in a block, with the order of testing being different across subjects. For each such block, the values of m to be tested were presented in a random order.

Because it is often difficult, if not impossible, to maintain contact with student subjects throughout the course of a long experiment, only 1 subject, G.R. (one of the authors), served in all conditions. Three of the other 4 listeners were paid undergraduates and 1, B.D., was a graduate student of composition in the Department of Music at the University of California.

RESULTS

Because there are so few data on the pitches of trains of high-frequency clicks (an exception being those from Hoekstra, 1979), we felt it necessary to control for the possibility that judgments would be based on information

Figure 4. Thresholds for changes in click rate ($\Delta\text{CR}/\text{CR}$) as a function of the number of periods in the click train (m). Both are plotted logarithmically. Three click rates are presented, 150 Hz (triangles), 250 Hz (circles), and 400 Hz (squares). The center frequency was fixed at 3500 Hz, and the data were collected in quiet. To aid in comparison, the top two dashed lines are as in Figure 3. Data for 3 subjects are presented.

Figure 5. Thresholds for changes in click rate ($\Delta CR/CR$) as a function of the number of periods in the click train (m). As Figure 4, except that lowpass noise was continuously present.

other than the envelope's periodicity. Before examining the issue of primary concern, the effect of duration on the discrimination of period, we will show that the use of a roving center frequency and the addition of low-frequency noise were unnecessary precautions.

Figure 3 shows comparisons between conditions in which the center frequency was either fixed or roving. Only wideband (short-duration) clicks were used. Data for the two CRs, 167 (top) and 250 (bottom) clicks/sec, are drawn separately. The three panels present data from 3 listeners. Open points are from conditions in which the center frequency was fixed at 3500 Hz; closed points are from cases in which it was allowed to rove. The dotted lines indicate a slope of -0.5 . The ordinate is a logarithmic plot of the Weber fraction, $\Delta CR/CR$; the abscissa is a logarithmic plot of the number of periods in a train, m . Except for producing especially high variability in the performance of Subject B.D., there was no apparent effect of roving the center frequency; differences between these two conditions were nonsignificant [$F(2,4) = 0.24$]. More importantly, there was no interaction between CR and the number of periods [$F(3,6) = 2.98$], with the functions relating $\log \Delta CR$ and $\log m$ being reasonably linear, with average slopes of about -0.5 (Table 2, upper panel). This differs from lateralization results in which slopes of the log threshold, $\log n$ functions depend on rate.

Figures 4 and 5 show the effects of introducing lowpass noise. Here, the range of rates tested was expanded to include 150, 250, and 400 clicks/sec, with the latter requiring the use of clicks of shorter durations and hence wider bandwidths. Figure 4 presents the data obtained in quiet; Figure 5 presents those collected in the presence of lowpass noise. The parameter is CR, with triangles, circles, and squares indicating rates of 150, 250, and 400 clicks/sec, respectively. Again, the dotted lines indicate a slope of -0.5 . While it seems that the absolute values of the thresholds were slightly elevated by the noise, particularly when the CR was 150 Hz, these changes were nonsignificant at the .05 level [$F(1,2) = 12.07$]. This is consistent with Hoekstra's (1979) obser-

vation that lowpass noise did not affect the relationship between the discriminability of period and the center frequency of the signal.

Again, there was no apparent interaction between $\log \Delta CR$ and $\log m$ [$F(4,8) = 1.38$]. This lends credibility to the conclusion that the functions are reasonably linear with slopes of close to -0.5 (Table 2, lower panel).

DISCUSSION

Effects of Roving the Center Frequency

When we first listened to these stimuli, we were struck with the strong sense of pitch they produced, despite the fact that most of the energy was concentrated at rather high harmonics. We have found this to be true of trains of Gaussian pulses, even when the center frequencies are much higher than the ones used here (albeit, with increasingly higher harmonic numbers, there is a decrease in the frequency of tones set to match the pitch of the complex; Terhardt, 1971; Wallicer, 1969). Indeed, the pitch remains strong even when lowpass noise was present in the "dominance region" for pitch (Plomp, 1967; Ritsma, 1967). Although we have not examined pitch strength directly, we are inclined to think that the surprisingly strong pitch is due to either the Gaussian filter shape or the relatively wide bandwidth used (Wightman, 1973). Because of the pitch salience, we were not surprised when the roving f_{cen} turned out to have little effect, strengthening our conviction that listeners were attending to periodicities rather than discriminating matched components as discussed in the Method section.

Effects of the Bandwidths (Durations) of the Individual Clicks

Wideband clicks were used here solely because their shorter durations would allow for testing at 400 clicks/sec. Because of their relatively late introduction into the experiment, no direct comparisons across bandwidths can be made. However, one should note that performance tended to be better with the wideband clicks, a finding

Table 2
Slopes of the Log-Relative Threshold, Log m Functions
for the Longer Click Trains

BW	LP Noise	Center Freq	Click Rate	Subjects			Averages
				B.D.	S.V.E.	G.R.	
Narrow	no	Fixed	167	-.39(.43)	-.40(.90)	-.67(.89)	-.51(.81)
Narrow	no	Fixed	250	-.19(.46)	-.31(1.0)	-.63(.93)	-.42(.92)
Narrow	no	Roved	167	-.50(.90)	-.26(.56)	-.69(.99)	-.53(.97)
Narrow	no	Roved	250	-.72(.75)	-.29(.88)	-.56(.77)	-.56(.90)
				Subjects			
				J.O.	L.G.	G.R.	
Wide	no	Fixed	150	-.50(.90)	-.58(.80)	-.52(.83)	-.53(.94)
Wide	no	Fixed	250	-.69(.96)	-.46(.74)	-.52(.94)	-.56(.92)
Wide	no	Fixed	400	-.57(.92)	-.54(.91)	-.75(.94)	-.63(.96)
Wide	yes	Fixed	150	-.44(.92)	-.38(.76)	-.43(.96)	-.42(.93)
Wide	yes	Fixed	250	-.55(.97)	-.44(.83)	-.17(.97)	-.41(.94)
Wide	yes	Fixed	400	-.47(.94)	-1.0(.93)	-.66(.79)	-.77(.93)

Note—Individual subject and averaged data are shown. Relative thresholds are the obtained threshold (for each subject and condition) divided by the threshold for that subject and condition found with the largest m . Values of the squared correlation coefficients are indicated in parentheses. BW=bandwidth, LP=lowpass.

consistent with results both in lateralization (Wenzel, 1984) and in rate-discrimination (Richards & Hafter, 1983).

Effects of the Lowpass Noise

Although nonsignificant, there appeared to be a slight rise in the discrimination thresholds due to the presence of the lowpass noise. If so, one could argue that the noise interfered with effective usage of the lowest components in the signals. Considered in conjunction with the special importance attributed to lower harmonic numbers in the determination of pitch (e.g., Plomp, 1967; Ritsma, 1967), it might further lead to speculation that our subjects applied heavier weightings to the lower harmonics, even though those amplitudes were relatively small. Nevertheless, it is important to note that while discriminability was marginally reduced when lowpass noise was present, there was no effect on the relationship between log threshold and log m .

Effects of Click Rate on the Absolute Thresholds

In Figures 4 and 5, we see that although the differences between thresholds at 250 and 400 clicks/sec were not large, there was a marked reduction in performance at the lower rates. Decreasing the CR decreases the spacing of the spectral components, and there are at least two ways in which this might affect discrimination. For one, it has been suggested that the pitch derived from higher harmonic numbers is simply less salient (Goldstein, 1973). Second, with the level of each individual click set to 40 dB SPL, each of the more densely packed spectral components would, of necessity, be less intense. Unfortunately, the importance of pitch salience for discrimination is impossible to test directly, and, because we used only one signal level, we cannot test the importance of the individual component intensities.

Effects of Increasing Duration

An appealing feature of the log threshold, log number function is that its slope reflects the efficiency with which information is transmitted throughout the click train, regardless of the stimulus parameter being tested. Thus, we have compared the efficiency with which information is extracted across such different stimuli as interaural differences of time and level. Table 2 shows the least squares fitted slopes to all of the conditions tested. Squared correlation coefficients (r^2) are indicated in parentheses. In order to visualize the comparison of slopes across conditions, data from Figures 3, 4, and 5 were replotted as *relative* thresholds, defined as the ratio of the actual value of each $\Delta CR/CR$ divided by the $\Delta CR/CR$ found for the largest number of periods tested for that particular condition. The scaling of performance relative to that with the largest m was done separately for each listener and condition before averaging. By parsing individual differ-

Figure 6. Average relative thresholds are indicated as a function of the number of periods for click rates of 167 Hz (triangles) and 250 Hz (circles). The values are based on the average of 3 subjects and both center frequency conditions (fixed and roved; Figure 3).

Figure 7. Average relative thresholds are indicated as a function of the number of periods for click rates of 150 Hz (triangles), 250 Hz (circles), and 400 Hz (squares). Open symbols indicate that thresholds were obtained in quiet (top panel, derived from Figure 4), and closed symbols indicate the presence of lowpass noise (bottom panel, derived from Figure 5).

ences in sensitivity, comparison across subjects is facilitated. Figure 6 is based on the data from Figure 3, averaged across the fixed and roving f_{cen} conditions and averaged across all subjects. Figure 7 results from Figures 4 and 5, preserving the distinction between those obtained with (bottom panel) and without (top panel) low-pass noise.

When comparing performance with signals of various lengths, one must consider at least two sources of variance. The first might be thought of as decision variance; it is added subsequent to analysis in the sensory channels, and so is unaffected by duration. For shorter durations, it generally is quite small relative to variation in the sensorineural code, and thus of little influence. Here one would expect to see its presence only with long durations where it sets the floor in performance. The more important factor for perceptual processing is the sensory noise added to the neural code. This source of variance should be reduced by successive sampling of the stimulus information so that the rate by which performance grows with increasing signal duration can be used to infer the effectiveness with which successive portions of the signal are transduced into neural code. With this in mind, we note that despite variability across subjects, it is clear that the averaged slopes are close to the value of -0.5 ; this signifies that rate discrimination was based on information extracted uniformly from throughout the duration of the signal (Equation 10).

Comparisons With Past Research

Were the signal durations to increase without bound, an asymptotic performance floor would undoubtedly have been reached. The current data do not allow an unequivocal estimate of the point at which such a floor is reached, nor are we able to determine whether the asymptote is dependent on the signal duration versus the number of periods presented. We may, however, posit a minimum estimate of 50 clicks, or 330 msec (on the basis of a CR of 150 Hz). In contrast, both Yost (1980) and Buunen (1980), who studied the interaction of signal duration and pitch strength for ripple noise, demonstrated that, independent of the time delay employed, pitch strength fails to grow as the signal duration exceeds about 200 msec. Furthermore, the relative threshold for the discrimination of changes in the time delay of ripple noise is about 0.03 (Yost, Hill, & Perez-Falcon, 1978), whereas the terminal value obtained here is about 0.002. It is worth noting that there are at least two key differences between our stimuli and ripple noise stimuli. First, our stimuli are periodic (and deterministic). Second, our stimuli are relatively narrow band. The relative importance of these two aspects is unknown, and either could effect a change in the mechanism recruited for the discrimination task.

In an experiment similar to ours, Hoekstra (1979) examined the discriminability of changes in the rate of filtered click trains (1/3 octave bandpass filtered, 600 msec duration). For a CR of 200 clicks/sec, relative thresholds (70% correct discrimination) of approximately 0.001 and 0.015 were obtained for filters centered at 2000 and 4000 Hz, respectively. Our terminal estimate of 0.002 (75% correct discrimination) is comparable.

Finally, we shall compare our thresholds with the values obtained by Moore (1973), who determined the jnd (75% correct) for pure tones of varying durations. The average relative threshold for a 250-Hz tone presented for 40 msec ($m=10$) was 0.006. For signal durations of 200 msec ($m=50$), the average relative threshold was 0.003. In the current experiment, "wide" clicks presented at a rate of 250 clicks/sec yielded average relative thresholds of 0.004 and 0.0017 for signal durations of 48 and 192 msec, respectively. Thus, our data and Moore's tonal data are reasonably close in both magnitude and the effect of signal duration on the threshold (on a log duration vs. log threshold plot, Moore's data yield a slope of -0.43). For 2000-Hz tones (1500 Hz lower than the center frequency of the clicks used in the current experiment), Moore obtained average jnds of about 5.5 and 4.5 Hz for signal durations of 40 and 200 msec, respectively (a slope of -0.13 on a log duration, log jnd plot). Four-thousand-hertz tones led to average jnds of 18.9 and 14.6 Hz for signal durations of 40 and 200 msec, respectively (a slope of -0.16 on a log threshold, log jnd plot). Thus, for discriminability, changes in signal duration affect high-frequency clicks and tones at the frequency of the (missing) fundamental similarly; and changes in the

signal duration affect high-frequency clicks and high-frequency tones differently.

Comparisons With Lateralization and a Speculation About Adapting and Nonadapting Channels

As discussed in the introduction, for lateralization of trains of clicks, the consistent finding has been that for higher CRs, the listener relies increasingly on information coded in the signals' onsets. Additional evidence has suggested that the site of the "binaural adaptation" is in the auditory periphery, prior to binaural interaction (Hafters & Buell, 1985; Hafters et al., in press), and one reason for the present experiment was to see if temporal processing that did not require binaural interaction would show a similar special reliance on the onset.

Direct comparisons between results from the two kinds of tasks are instructive. From lateralization, discrimination of interaural delays produced average slopes of the log Δ IDT, log n plots of -0.38 for a rate of 200 clicks/sec and -0.22 for a rate of 500 clicks/sec (Hafters & Dye, 1983); similarly, discrimination of interaural differences of level produced average slopes of the log Δ IDL, log n plots of -0.40 for rates of 200 clicks/sec and -0.29 for rates of 500 clicks/sec (Hafters et al., 1984). This differs greatly from the results found here for discrimination of click rates where slopes of log Δ CR, log m functions seem independent of click rate. Thus, it would appear that the information-reductive process responsible for "binaural adaptation," although thought to occur prior to binaural interaction, does not affect the discrimination of rate-dependent pitch.

These comparisons raise an interesting possibility. Here we have a case where very similar stimuli, that is, trains of high-frequency clicks, are treated very differently, depending on what kind of information is being extracted from them. Suppose that there are two types of channels in the monaural periphery. Neurons of the first kind carry information to be used for spatial hearing. They are somewhat "phasic" in response to high rates of stimulation, passing on to the binaural nervous system interaural information contained primarily in the signal's onset. The others are more "tonic," sending forward information to be used for discrimination of pitch that is drawn from throughout the stimulus. According to this view, the pathways that carry the message "what is the sound" monitor the signal continuously, whereas those responsible for tracking its direction rely on information in its onset. The notion of an anatomical as well as a functional dichotomy in the early response to high-frequency envelopes is intriguing, but it will require direct studies of electrophysiology for confirmation or refutation.

SUMMARY

1. Studies of lateralization based on interaural differences in the envelopes of modulated high frequencies have shown that as the envelope rate increases, the lateraliza-

tion threshold is based increasingly on information derived from the stimulus onset. We have called this process "binaural adaptation."

2. Because previous experiments suggested that the neural site of "binaural adaptation" is in the auditory periphery, we questioned whether extraction of information about the signal's pitch would show a comparable reliance on the onset. Thus, listeners were presented with stimuli similar to those used in lateralization experiments, namely trains of filtered clicks centered at high frequencies, only here, they were asked to discriminate between trains with slightly differing periods.

3. A battery of control conditions included the use of low-frequency noise to prevent use of artifactual cues due to nonlinear distortions and of a roving-center-frequency technique designed to prevent discriminations based on comparisons between the levels of individual harmonic frequencies. Neither precaution proved essential.

4. Of primary interest was the effect of click rate on the relationship between discrimination and signal duration since it is from such functions that one can infer the relative efficacy of each period in a train. The idea is that differences in performance between trains of differing lengths are due to the adoption of additional samples of the information into the sensory code. Accordingly, integration of information throughout the train should result in a square-root reduction in the combined internal noise and, hence, a square-root reduction in threshold with increased duration.

5. The primary result was that unlike the case with lateralization, the information extracted for rate discrimination grew uniformly with stimulus duration for all of the click rates tested. It is suggested that there may be separate channels used to carry information for spatial hearing and for discrimination of pitch.

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