Detection and discrimination thresholds for auditory periodicity

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Complex periodic auditory signals, produced by the Guttman-Julesz procedure of repeating segments of random noise, were employed to address the low region of auditory periodicity. Periodicity detection and discrimination tasks were examined with a common experimental procedure and a common measure of thresholds. Typically, detection and discrimination performance suffer at extremely low periodicities, presumably because of the extremely close spacing of harmonics throughout the auditory spectrum. Interaural phase effects are extremely weak for these signals, being largely confined to threshold-detection tasks. Despite qualitative phenomenological differences for different periodicity regions, detection and discrimination functions show no sharp discontinuities over a wide range of periodicities.

Guttman and Julesz (1963) introduced a procedure for generating complex auditory signals with a defined fundamental periodicity. In their procedure, samples of random noise are periodically repeated. The repetition period defines the fundamental frequency. Different waveforms produce different overtone structures. An important feature of these signals, stressed both by Guttman and Julesz and by Warren (1982) and his colleagues, is that the signals access lower auditory periodicities than can be accessed by pure tones alone.

A wide range of phenomenological descriptors has been used to describe the perception of different periodicity regions produced by repeated random waveforms. The descriptors, and their approximate periodicity ranges, for the listeners of Guttman and Julesz (1963) and of Warren and Bashford (1981) are: apparent periodicity achieved only with directed effort, 0.1–0.5 Hz; apparent periodicity without effort, 0.5–1.0 Hz; whooshing, 1–4 Hz; motorboating, 4–25 Hz; rough noisy pitch, 25–50 Hz; smooth noisy pitch, 50–100 Hz; melodic pitch, 100–4000 Hz; and amelodic pitch, above 4000 Hz. In addition to different descriptors for different periodicity regions, auditory theory assigns different neural coding procedures to different periodicity regions. In particular, temporal coding is associated with low periodicities; spectral frequency, or place, coding with high periodicities.

This paper concerns the exploration of several auditory detection and discrimination tasks with these signals. The eventual goal is to extend the auditory psychophysics of pure tones to a wider range of complex auditory signals.

METHOD

Signals

Pseudo-random number sequences were generated in a personal computer (IBM/AT), sampled at 80 kHz, converted to voltages (Data Translation DT2821), and transduced to sound at a comfortable listening level by means of a binaural headset (Koss PRO-4). The pseudo-random number sequences were generated by a uniform "boxcar" probability distribution (Microsoft Corporation, 1986). The periodicity of the pseudorandom sequences exceeded the lowest signal periodicity by many orders of magnitude. Although the instantaneous amplitude distribution is not exactly that of a Gaussian white noise, its frequency spectrum is continuously wide-band and sounds like white noise. Except for the low-pass frequency characteristic of the earphone (typically lower than the 20–80 kHz sampling rate), no additional filtering was introduced in order to avoid aliasing.

Periodic "signals" were produced by repeating sequences of random numbers. For example, at a sampling rate of 80 kHz, repeating a list of 8,000 random numbers produces a periodicity of 10 Hz ($80,000/8,000 = 10$). The resulting spectral frequency distribution of a repeated random waveform is that of a complex tone with a lowest component frequency equal to the repetition or fundamental frequency, and with a distribution of higher harmonics determined by the repeated waveform. A third-octave analysis of the repeated random waveform is presented in Warren (1982, pp. 79, 83, 93). The fundamental temporal periodicity is reflected throughout the auditory frequency range. "Noise" was produced in the same manner, but without repetition. On each observation, an independent random selection was carried out for signal and for noise. Signal and noise were presented simultaneously. The signal duration was the longer of 100 msec or four pattern replications.

The same distribution of amplitudes was sampled for signal and for noise. The output was a weighted sum of the signal and the noise. The weighting of the signal, s , was complemented by the weighting of the noise, $(1 - s)$, to yield a constant sum [$s + (1 - s) = 1.0$]. For example, if the procedure called for a signal weighting of 0.8, the noise weighting was 0.2, which was a signal-to-noise (S/N) ratio of 4.0 or, in decibel terms, 12 dB.

Tasks

In a single observation interval, one of two sounds was presented to each listener for identification. The task of the listener was to

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Table 1
Experimental Tasks

Test A	Test B	Test C	Test D
Periodicity Detection (Background noise)	Purity Detection	Periodicity Detection (Background periodicity)	Periodicity Discrimination
P+N (periodic)	N+P (impure)	160 Hz + P (tonal)	P ₁ + N (high)
N+N (nonperiodic)	P+P (pure)	N+P (noisy)	P ₂ + N (low)

identify the sound in terms of a binary response. Immediate feedback was given after each response. The composition of the two sounds differed with the specific task. For example, in the detection of periodicity against a noise background, schematically shown as Test A in Table 1, one sound consisted of "periodicity plus noise"; the other consisted of "noise alone." (The combination of two independently generated noises ensured that the generation procedure was the same for two sounds.) The listeners' task was to identify each sound as either "periodic" or "noisy." Table 1 also outlines the other tasks with their associated signals and binary responses. The purity-detection task (Test B) might also be considered as noise-detection task against a periodic background. The periodicity-detection task (Test C) might also be considered as a discrimination test for a periodicity of 160 Hz versus a wide-band noise against a variety of periodic backgrounds. Test D was a periodicity-discrimination test against a noise background.

In addition to periodicity variables, four extreme conditions of interaural phase were examined: 1 = SΘNΘ, 3 = SΠNΘ, 5 = SΘNΠ, and 7 = SΠNΠ, where Θ implies in phase at the two ears and Π implies out of phase, S implies the first component of each additive combination of Table 1, and N implies the second component. Interaural phase is of concern because binaural detection tests with pure tones produce large interaural threshold differences.

Interaural phase effects can be contrasted in terms of the four-way contrast cited above or in terms of the following two-way contrasts: signal phase (1+5 vs. 3+7), noise phase (1+3 vs. 5+7), or the S/N relations of homophasic versus antiphasic (1+7 vs. 3+5).

Procedure

An adaptive procedure varied the relative signal level to converge upon 70.7% correct responses (Levitt, 1971). The "step size" in the adaptive procedure was 0.1 times the previous relative signal level. For example, with an observation at a relative signal level of 0.50 (a S/N ratio of 0 dB), the next observation was carried out at a relative signal level of 0.45, 0.50, or 0.55, depending upon the correctness of the listener's response and the sequential response contingencies in the adaptive procedure. The step size was highly nonlinear, in decibel terms: approximately 0.9, 1.7, and 20.8 dB for increments in relative signal levels of 0.1, 0.5, and 0.9, respectively. A "reversal" marked the transition between two successive correct responses and an incorrect response (or the converse). A "run" consisted of 15 successive reversals, following an initial two reversals. A "threshold" is the average relative signal level over the run. A typical run consisted of about 45 observations. All calculations were based upon threshold signal levels before conversion to S/N ratios.

Experimental Design

Each test attempted to cross each condition of each variable with each condition of the remaining variables. Table 2 lists the number of conditions for each variable. The strength of each variable was assessed by analysis of variance (SAS, Inc., 1985). Multiple-comparison post hoc tests employed the Waller post hoc procedure following the analysis of variance (SAS, Inc., 1985).

Listeners

A single group of 5 listeners, university music majors and the author, completed all tests. They were highly experienced, having

completed auditory psychophysical tasks in at least two semesters (5–10 h per week).

RESULTS

Overall Results

Table 3 presents the percentage of the total variance associated with each of the experimental factors in the separate tests. The associated significance level is listed in parentheses, or is nonsignificant (n.s., $p > .05$), or otherwise is significant at $p < .0001$. Interactions that included interaural phase employed the component of interaural phase with the highest statistical significance. The error term includes all insignificant variables. The *RMSE* is the root-mean-square error of a single observation, in units of relative signal level, after extraction of systematic variance.

The major result of Table 3 is that signal periodicity is the major contributor to experimental variance in periodicity detection with a noise background (Test A), in purity detection (Test B), and in periodicity discrimination (Test D), but contributes less variance in periodicity detection with a restricted range of background periodicities (Test C). Although the same listeners participated in all tests, the proportion of variance associated with listeners varied across tests.

Separate Tasks

The threshold S/N ratio for periodicity detection is presented in Figure 1. The symbols reflect the interaural phase relation. Thresholds decrease, with fundamental frequency leveling off at 160–320 Hz at S/N = -7 or -8 dB. The change in threshold is about 24 dB over three octaves, or about 8 dB/octave. Noteworthy is that interaural phase effects for these signals, although statistically significant, are small. Based upon the average threshold signal level, the antiphasic condition (marked as 7 in Figure 1) demonstrated an average lower threshold

Table 2
Experimental Plan for Four Tasks

Variable	Task				
	A	B ₁	B ₂	C	D
Periodicity	15	28	17		9*
Interaural Phase	4	4	4	4	4
Periodicity Ratios				24	6*
Listeners	5	5	5	5	5
No. of Thresholds	300	560	340	480	1,040

Note—Entries are the number of conditions per variable. *Actually 52 combinations including intermediate periodicities.

Table 3
Factors Contributing to Experimental Variance

Factor	Test			
	A	B	C	D*
Periodicity	56.0	57.0		21.8
Interaural Phase	n.s.	n.s.	n.s.	n.s.
S Phase	n.s.	n.s.	n.s.	n.s.
N Phase	n.s.	n.s.	n.s.	n.s.
S/N Relation	5.0 (.002)	n.s.	8.0 (.02)	2.6 (.002)
Periodicity Ratio Interactions			6.6	41.4
a * b	n.s.	n.s.	n.s.	n.s.
a * c				0.4 (.04)
b * c	n.s.	n.s.	n.s.	n.s.
Listener Interactions	34.5	40.0	68.9	29.8
a * d	n.s.	1.7	2.0 (.05)	0.7 (.0003)
b * d	n.s.	n.s.	4.8 (.01)	n.s.
c * d				2.1
Error	3.5	1.3	9.7	1.2
RMSE	0.076	0.069	0.109	0.082

Note—Entries are percentages of total variance with tests. Numbers in parentheses represent the associated significance level. *For 30 combinations of periodicity and periodicity ratio.

advantage of only about 0.9 dB over the homophasic condition (marked as 0 in Figure 1).

Thresholds for purity, or perhaps better named impurity, detection are presented in Figure 2 for two separate test series, B₁ and B₂. The discrepancy between the two series at high periodicities is related to details of the experimental procedure.¹ The asterisk represents the threshold at 5 Hz in Test 6. Large threshold changes are observed with target frequency for purity detection. A 30-

dB shift over a three-decade range, or about 3 dB/octave, is obtained in favor of higher target periodicities. No significant interaural phase effects were observed for purity detection.

Figure 3 considers the discrimination between one of two targets: a nonrepeated noise and a repeated random waveform of 160 Hz. Each target was presented against the same background periodicity. The target/background (T/B) ratio for the 160-Hz target is presented on the ab-

Figure 1. Periodicity-detection thresholds above a noise background. The symbols reflect the indicated interaural phase conditions (0 = homophasic; 7 = antiphasic).

Figure 2. Purity-detection thresholds between noise and periodicity over a periodicity background. The symbols reflect two different test series (see text and Note 1).

scissa. For example, a T/B ratio of 0.25 reflects a background periodicity of 640 Hz; and a T/B ratio of 4 reflects a background periodicity of 40 Hz.

Over a 64-fold variation in the periodicity ratio, and hence, in the background periodicity, there is a total threshold variation of only about 10 dB. This contrasts with a range of tone-on-tone masking at moderate sound

Figure 3. Periodicity-detection thresholds for the discrimination of a 160-Hz periodicity from a wide-band noise, each 160 Hz presented above a periodicity background.

Figure 4. Expansion of Figure 3 for the periodicity region near 1.0.

Figure 5. Periodicity-discrimination thresholds for different reference periodicities. The symbols reflect the periodicity ratio of the comparison signal (0 = 1.015; 1 = 1.031; 2 = 1.062; 3 = 1.125; 4 = 1.25; 5 = 1.5).

levels of over 50 dB (Wegel & Lane, 1924). Moreover, pure tones demonstrate substantially narrower masking patterns than do bands of noise (Egan & Hake, 1950). Except for irregularities for T/B ratios near 1.0, there is a trend for lower thresholds for higher background periodicities (lower T/B ratios) than for lower background periodicities (higher T/B ratios). The greater masking effectiveness for lower background periodicities has long been noted for tone-on-tone masking (Wegel & Lane, 1924). The periodicity region for T/B ratios near 1.0 is shown in expanded detail in Figure 4. Within this narrow range, the local minimum for T/B = 1.0 may reflect judgments about the purity of the 160-Hz target. Over all conditions, the homophasic-antiphase contrast was again small, averaging about 0.9 dB, but statistically significant.

Periodicity-discrimination thresholds are presented in Figures 5 and 6. Figure 5 presents periodicity thresholds for different reference periodicities; the symbols on the graph indicate the periodicity ratio. (The comparison periodicity is the reference periodicity divided by the periodicity ratio.) The reference periodicity is therefore the higher of the two periodicities. Figure 6 interchanges the abscissa and parameter of Figure 5.

Figure 5 suggests that minimum thresholds are obtained for reference periodicities in the vicinity of 1000 Hz, with sharply larger thresholds for lower, and for higher, periodicities about 1000 Hz.

By comparison, Cullen and Long (1986) examined the sensitivity to changes in rate of periodic pulse trains in

Figure 6. Periodicity-discrimination thresholds for different periodicity ratios. The symbols reflect the reference periodicity in one-octave bands (0 = 40 Hz; 1 = 80 Hz; 2 = 160 Hz; 3 = 320 Hz; 4 = 640 Hz; 5 = 1280 Hz; 6 = 2560 Hz; 7 = 5120 Hz; 8 = 10 kHz).

the absence of noise. Lowest absolute rate thresholds for unfiltered pulse trains were obtained for fundamental repetition rates of 100–200 Hz, although thresholds expressed in terms of the relative rate, $\Delta r/r$, continued to decrease for repetition rates to 800 Hz. When the contribution of the lower harmonics was reduced by high-pass filtering, absolute rate thresholds favored the higher fundamental repetition rates.

Table 4 presents the results of multiple-comparison tests of significance (Waller test following analysis of variance; SAS, Inc., 1985). Within each column reflecting separate periodicity ratios, reference periodicities that are assigned the same character are statistically equivalent (i.e., not significantly different). Periodicities assigned more than one character are equivalent to periodicities sharing the characters. For periodicity ratios of 1.25 and 1.5, with a large number of periodicities, the breaks in the alphabetic sequence (e.g., a c e) imply that conditions adjacent to the break are statistically equivalent. Table 4 tends to confirm the existence of a minimum region of periodicity thresholds in Figure 5.

Figure 6 suggests that lower thresholds are achieved with higher periodicity ratios, at least to 1.125. Table 5, with the general organization of Table 4, confirms the superiority of higher periodicity ratios and the leveling off after periodicity ratios of 1.125. (There is also a suggestion of higher thresholds at the largest periodicity ratio.) Interaural phase was significant for periodicity discrimination only in terms of the antiphasic-homophasic relation. The average difference was only 0.8 dB in favor of the antiphasic condition.

DISCUSSION

In independent detection and discrimination tasks with periodic random waveforms, interaural phase effects were found to be either nonsignificant or very small—on the order of 1.0 dB or less. This result contrasts with the extremely large interaural phase effects observed in detection tasks with pure tones (Durlach & Colburn, 1978). Small interaural phase effects have also been found in speech-intelligibility tests (Licklider, 1948), despite the preponderance of low frequencies in speech. The critical difference would thus appear to be whether the signals are wide-band or narrow-band. An extension of this view relates to the lateralization of signals near the detection threshold. With pure tones and highly trained subjects, it has been argued that detection in noise can be accomplished by noting a change in the phenomenal location of the signal. Indeed, interaural phase differences are identical whether obtained in a pure-tone detection task or in a pure-tone localization task (Haft, Bourbon, Blocker, & Tucker, 1969). Thus, the crucial feature for interaural phase effects in detection may be whether or not the signal can be discerned via localization. In these terms, the detection of periodic random patterns, especially when independent samples are drawn on successive observations, is probably not accomplished through changes in localization, at least not without specific training.

With respect to the role of localization, extremely large interaural phase effects have been observed for the lateralization, but not for the detection, of repeated random waveforms (Pollack, 1989). The absence of large inter-

Table 4
Multiple-Comparison Tests of Statistical Significance across Reference Periods for Periodicity-Discrimination Tests

Reference Period (in Hz)	Periodicity Ratio					
	1.015	1.031	1.062	1.125	1.25	1.5
40					g	f
80		c	c	c	f	e
160		c	b	b	ce	c
312	a	ab	a	a	ac	c
625	a	a	a	a	ace	a
1250	a	a	a	a	a	a
2500		b	a	a	a	a
5000			d	c	e	a
10000				d	h	g

Table 5
Multiple-Comparison Tests of Statistical Significance across Periodicity Ratios for Periodicity-Discrimination Tests

Periodicity Ratio	Reference Periodicity (in Hz)							
	40	80	160	312	625	1250	2500	5000 10000
1.015				e	d	d		
1.031		c	d	d	c	c	c	
1.062		b	c	c	b	b	b	c
1.125		a	a	a	a	a	a	b a
1.25	a	a	a	ab	a	a	a	a a
1.5	b	a	c	bc	a	a	a	a a

phase effects in the detection of repeated random patterns is *not* due to a failure to lateralize such signals. With appropriate time delays, these signals can be well localized. However, in the absence of added differential time delays, the subtle localization cues available in the pure-tone detection task are presumably unavailable for the detection of repeated random waveforms.

Comparison of periodicity detection in noise (Figure 1) with periodicity discrimination in noise (Figure 5) suggests that, at least for large periodicity ratios, periodicity discrimination is possible at S/N ratios approaching the detection threshold. The close approach to detection thresholds might, thus, also account for interaural phase effects in periodicity discrimination. Presumably, larger S/N ratios are required for the discrimination of small periodicity ratios because of the dissynchronizing action of the noise on the resulting signal.

Although detection and discrimination performance is typically poorer with lower periodicity frequencies than with higher frequencies, there is no evidence for a sharp discontinuity in the periodicity scale for any of the tasks. The small interactions of periodicity with other variables also suggests that the lower periodicity frequencies do not behave qualitatively differently than middle and higher periodicity frequencies, despite the large qualitative phenomenological differences at different periodicities (Guttman & Julesz, 1963; Warren, 1982).

The relative effectiveness of different periodicity regions depends upon the specific task configuration. For interference tasks, lower periodicities have the advantage over higher periodicities because the lowest frequency component is equal to the fundamental repetition frequency, and because harmonics are more closely spaced. For detection and discrimination tasks, higher periodicities are advantageous, again for the same reasons and because of the superior relative discrimination of the auditory system for intermediate frequencies (Scharf, 1970).

One reasonable assumption is that a repeated random waveform is equivalent to an amplitude-modulated noise, at least with respect to its envelope. On the basis of this assumption, the modulation-detection threshold might be expected to parallel the detection thresholds in Figure 1. The comparison would then be the modulation depth threshold for modulation detection with the S/N detection threshold in Figure 1. Whereas modulation depth thresholds increase at higher periodicities for amplitude-modulated noise (Rodenburg, 1977; Viemeister, 1977), the detection thresholds decrease at higher periodicities in Figure 1. Clearly, there is more to the detection of repeated random waveforms than detection of envelope periodicity alone. The strong pitch character at higher repetition frequencies is most likely due to the presence of spectral harmonics.

The purity (or impurity) experiment of Figure 2 examined how well the repeated waveform alone could mask the presence of the wide-band masking noise. Here, we

asked how well repeated waveforms serve as interference. With this task, the lower periodicities clearly produce more interference: successive harmonics are more closely spaced, and therefore more nearly approximate the continuous noise spectrum; the lowest frequency component in the repeated waveform is the fundamental repetition frequency, and jitter detection is superior at high, relative to low, periodic frequencies (Pollack, 1968).

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NOTE

1. There was a fundamental difference in experimental procedure for the two experimental series employed in the (im)purity-detection tests of Figure 2. Table 2 illustrates the procedure of Series 6. In symbolic terms, the contrast was between (N + P) and (P + P), where the first element in each term was under adaptive control. The equivalent contrast in Series 2 was between (P + N) and (P + P). First, consider an unbiased N/P threshold near 0 dB (i.e., with P = N = 0.5). Both

Series 2 and Series 6 would converge upon the same threshold. The adaptive step size in the threshold region would be identical at 0.05 in the two series. There would be little to distinguish between the two procedures. Now consider an unbiased N/P threshold near -19 dB (i.e., with $P = 0.90$ and $N = 0.10$). Series 6 would converge upon 0.10 with an adaptive step size of 0.01; Series 2 would converge upon 0.90 with an adaptive step size near 0.09. A finer measure of threshold sensitivity was, therefore, available in Series 6 than in Series 2 for extreme N/P

ratios. Figure 2 suggests that nearly comparable thresholds are obtained in the two series for N/P amplitude ratios of up to -12 dB, where $P = 0.80$ and $N = 0.20$. The results of the two experimental series, however, differ appreciably at more extreme N/P ratios.

(Manuscript received February 14, 1989,
revision accepted for publication August 30, 1989.)