Detection and recognition of intensity changes in tone and noise: The detection-recognition disparity*

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Recognition of increments vs decrements in auditory intensity improves with signal duration, relative to detection of increments and decrements. This effect obtains whether the background stimulus is a tone, noise, or a tone with noise masker, and is largely uninfluenced by the rise time of the signals. These data are inconsistent with detection models in which the O makes only one sensory observation during each observation interval, but can be described in terms of a neural timing model in which transients play a critical role.

The problems of detection (distinguishing a signal from the absence of a signal) and recognition (distinguishing signals from each other) are frequently investigated in similar paradigms and explained by similar theories (Luce, 1963; Tanner, 1956). Yet basic facts concerning the relation between the two are not well established. For example, it is not clear whether signals must always be recognized in order to be detected. Shipley (1965) argues from the results of her simultaneous detection and recognition experiment that this is true, but Lindner's (1968) data from a similar experiment do not support such a hypothesis.

Macmillan (1971) presented evidence of a different sort that the detection of signals was not completely dependent on their recognition. At short durations (less than about 100 msec), Os' ability to recognize whether a small increment or decrement in a pure tone background had been presented was comparable to their ability to detect those signals. At longer durations, their recognition performance exceeded their detection performance by approximately the amount predicted by a signal detection theory model in which the sensory effects due to the three signals (decrement, no change, and increment) are assumed to lie upon a single decision axis. This effect of duration on recognition, relative to detection, will be referred to as the "detection-recognition disparity."

The interpretation of these data suggested by Macmillan was as follows: In addition to an integrative detector (ID), which accumulates information about the stimulus over time and offers an identification of the signal, the O also has a *change detector* (CD), which

operates on signal onsets (and perhaps offsets), and thus does not integrate over time, and which only conveys information about the presence or absence of a signal, not about its identity. Both mechanisms combine in an unspecified manner to yield detection performance, but in recognition experiments only the ID is useful. In detection experiments, the CD will be relatively more important at short durations, where the ID is less reliable, so recognition performance will increase relative to detection as duration increases, i.e., the detection-recognition disparity will obtain. A model of this sort differs from most existing models of detection in proposing that detection (1) is in part nonintegrative, (2) is in part nonidentifying, and (3) involves more than one process.

The positing of more than one process is perhaps the most serious departure from tradition. One-process models have worked fairly well in auditory detection and should not be abandoned for an apparently more complex view unless the latter is clearly necessary. Leshowitz and Wightman (1972) have offered an explanation of Macmillan's (1971) data in terms of a one-process model, their (1971) variable filter model for tone-on-tone masking. They point out that the power spectra of the signals used in the experiment include nonnegligible amounts of energy (about 10% of the total) more than $1/(\text{signal duration})$ Hz from the signal frequency. Evidence from Leshowitz and Wightman (1971) suggests that Os can make use of this "energy splatter" to improve the detectability of short tones, presumably by moving an internal filter, of the sort customarily assumed by detection theorists (e.g., Green & Swets, 1966), off the signal frequency to a part of the spectrum where the signal-to-noise ratio is better. Since short tones have wider spectra than long ones, this adjustment will be most profitable at the shortest durations, improving detection at those durations. Recognition of increments and decrements, however, requires that the internal filter be moved to the signal frequency, where all the information relevant to a decision between increments and decrements is contained.

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This account is largely consistent with Macmillan's (1971) data [see Macmillan (1972) for exceptions], and apparently salvages one-process detection theories at the expense only of assuming considerable observer control over the presumed internal filter. However, the explanation rests heavily on the characteristics of the stimulus situation in Macmillan's experiment. The present paper reports the effects of altering the stimulus situation by using (in separate experiments): tonal signals with nonzero rise times (Experiments I and II), noise signals (Experiment III), and tonal signals in the presence of noise (Experiments IV and V). In these experiments, Leshowitz and Wightman's (1971) model predicts an elimination (or at least a weakening) of the detection-recognition disparity. To anticipate, although the results of these experiments are not inconsistent with the off-frequency listening hypothesis, they clearly indicate that this hypothesis cannot be the sole explanation of the detection-recognition disparity, since this effect appears in a number of conditions in which off-frequency listening is unprofitable. Thus, the data argue against the off-frequency listening hypothesis as an explanation of the detection-recognition disparity and strongly support the existence of a detection mechanism which does not identify signals and whose performance is independent of duration.

EXPERIMENT I: EFFECTS OF SIGNAL RISE TIME

If the detection-recognition disparity is due to off-frequency listening, then alterations in the spectra of the signals should alter the effect. One fairly simple method for altering the spectrum of a tonal signal, traditionally used by Es wishing to reduce energy splatter, is to gate the signal on with a nonzero rise time. This can be accomplished in either of two ways: by bandpass filtering the signal or by using an electronic switch to gate the signal on and off with a trapezoidal envelope. These two procedures do not have exactly equivalent effects on the signal spectrum, but they both serve to reduce the proportion of the energy that is off-frequency. Some examples of the spectra of both types of signals are given in Wightman (1971).

In this experiment, an electronic switch was used to vary rise time. Consider a 1,000-Hz tone that is gated on and off with a trapezoidal envelope and lasts 50 msec. To get a feel for the amount of energy splatter in such a signal, we compute the power spectrum and estimate the proportion of the energy falling within one critical bandwidth centered at the signal frequency.¹ For a 1,000-Hz signal, the critical band is approximately 160 Hz (Scharf, 1970, p. 162). For 0.5-msec rise times, the proportion of energy not in the band between 920 and 1,080 Hz is .023; for 5-msec rise times, this proportion is only .005. This gives an overall decrease in off-frequency energy of about 6.6 dB: thus, if the splatter is just detectable when the rise time is 0.5 msec,

it will not be detectable when the rise time is 5.0 msec.² A similar effect occurs with longer signals, although the proportions of off-frequency energy are lower. For a 300-msec burst, the two rise times above yield proportions of off-frequency energy of .003 and .0006.

Thus, increasing rise time, like increasing duration, decreases the proportion of the signal energy that is off-frequency. If the O is using the off-frequency energy in his decision, increasing the signal rise time should result in a decline in his performance (i.e., an increase in threshold). In addition, lengthening the rise time should reduce the detection-recognition disparity under this hypothesis: Without a significant proportion of energy off-frequency, the O should be forced to attend to the center frequency in both detection and recognition conditions, and his recognition performance should not improve as much with signal duration relative to detection performance.

Procedures

Two Os, one of whom was the investigator, served individually: O A.B. was paid at an hourly rate. Os sat in a double-walled IAC acoustic chamber, and stimuli were presented to them through PDR-10 earphones. At least 8 h of practice were given before any data were collected, and most experimental conditions were sampled in this period.

A 1,000-Hz tone was presented continuously to the O's right ear at 62 dB SPL. Signals were increments and decrements in the amplitude of the background tone and were turned on by an electronic switch (Grason-Stadler 829S61). Signal duration (25, 50, 100, and 300 msec) and rise time (0.5, 1.0, and 5.0 msec) were varied. All signals of the same nominal duration were adjusted in duration so that their energies were equal: a signal with a nominal duration of T sec and rise time of r sec was actually $T + 4r/3$ sec long from onset to offset.

Each two-alternative temporal forced-choice trial began with a faint warning click to the O's left ear. The first signal interval followed 1.5 sec after the click, and the second interval was spaced so that the time between the end of a signal in the first interval and the beginning of a signal in the second interval was always 750 msec. The signal intervals were marked by faint, brief (10-msec) lights on the O's response panel. The O responded by pushing one of two microswitches, and immediate feedback was provided on the response panel. The response initiated the next trial; this procedure produced one trial in approximately 5 sec. The two possible stimulus events on each trial were always equally likely.

Experimental sessions lasted 90 min and were broken into two or three parts by short breaks during which the O could leave the chamber. Trials were presented in blocks of approximately 100; the first block of trials each day was practice and was not included in the analysis. Os served about 5 days per week.

A single experimental session consisted of increment detection, decrement detection, and increment-decrement recognition at the same signal duration and rise time. The two detection conditions were always presented first (sometimes increments first, sometimes decrements). An up-down procedure was used to estimate the "threshold" intensity as follows: A block of trials began with the signal level as close as possible to threshold, based on practice data. If the O made five correct responses before he made two incorrect ones, the signal level was decreased; otherwise it was increased. The step size was approximately constant, as measured in terms of $\Delta v/v$, the proportional change in voltage represented by the signal, and was equal to .01.³ Two blocks of 100 trials each were run, and the

Table 1
Results of Experiment I: Effects of Rise Time on Detection and Recognition of Increments and Decrements in a Pure Tone

Rise Time (Msec)	Duration (Msec)	O AB				O NM			
		Increment Threshold (dB)	Decrement Threshold (dB)	Percent Correct in Recognition	Repliation?	Increment Threshold (dB)	Decrement Threshold (dB)	Percent Correct in Recognition	Repliation?
0.5	25	-9.3	-9.5	80	x	-7.6	-6.5	76	x
	50	-10.8	-10.5	80	x	-9.0	-8.6	73	
	100	-11.6	-11.9	81	x	-9.9	-9.3	91	x
	300	-13.4	-13.3	100		-10.9	-9.4	93	
1.0	25	-8.7	-7.5	77		-6.6	-6.4	81	x
	50	-11.4	-9.8	73	x	-9.4	-8.6	69	x
	100	-11.2	-10.5	79		-10.5	-9.3	82	
	300	-13.8	-10.6	94		-11.2	-10.6	95	
5.0	25	-8.9	-7.9	79	x	-6.7	-6.6	89	x
	50	-10.1	-10.2	78		-9.1	-7.7	78	x
	100	-11.9	-10.8	70		-9.2	-8.6	88	
	300	-12.9	-10.8	93		-11.7	-10.9	91	

mean of the pooled data was used to estimate the threshold.⁴

In the recognition condition, each trial was either an increment followed by a decrement or a decrement followed by an increment; the intensities used were the thresholds estimated in the detection conditions. Two recognition blocks of 100 trials each were run.⁵

Results and Discussion

Table 1 gives the threshold increment and decrement, measured as $10 \log (\Delta I/I)$, where I is the background power and ΔI the difference between background power and background-plus-signal power; the table also gives the percent correct in recognition. For most conditions, the detection-recognition disparity appears: percent correct in recognition is at about the level of detection performance at the short durations, but about 90% at the long durations: detection performance is assumed constant (73.5% correct) at all durations. However, there are some nonmonotonicities in the recognition data, and for the 5-msec rise time condition, N.M. does not clearly show the detection-recognition disparity. The apparent difference between the two Os could conceivably reflect the use of off-frequency listening by N.M. but not by A.B. Inter-O differences are not surprising when performance depends on the O's listening strategy.

At short durations (25 and 50 msec), the thresholds for the fast rise-time conditions tend to be lower than for the slower rise-time conditions: The slopes of the threshold vs log rise time functions for these two durations differ significantly from zero ($p < .05$, two-tailed t test). For longer signals, there seems to be little difference. This is consistent with the data of Garner (1947) and Creelman (1964), both of whom found that short tones were slightly less detectable when they were bandpass filtered (and thus had nonzero rise times).

EXPERIMENT II: EFFECTS OF SIGNAL RISE TIME AND FREQUENCY

The second experiment was similar to the first. Rise time was either 1 or 10 msec. The effects of this variation on the percentage of signal energy outside the critical band are similar to the effects of the variation from 0.5 to 5.0 msec in Experiment I. For a 250-Hz signal with a duration of 50 msec and a rise time of 1 msec, the proportion of the energy outside the critical band (200-300 Hz; see Scharf, 1970) is .034; for an otherwise identical signal with a 10-msec rise time, this proportion is .003.

Signal frequency was also varied in Experiment II. Although the width of the spectrum of a short tone does not vary much with frequency, the width of the O's critical band varies considerably. Thus, at 4,000 Hz, Scharf (1970) estimates the critical band to extend from 3,700 to 4,400 Hz. At this frequency, changing the rise time of a 50-msec burst from 1 to 10 msec changes the proportion of energy outside the critical band from .0014 to .00001. Thus, the amount of off-frequency energy, estimated in this manner, is very slight. The effect of rise time on this splatter is substantial, but it is not obvious that the O will be sensitive to such small amounts of energy.

Procedures

This experiment differed from the first experiment in the following ways: (1) The frequencies used were 250 and 4,000 Hz. (2) The rise times used were 1 and 10 msec. (3) The durations used were 50, 100, and 300 msec. In cases where recognition performance had not reached a high level at 300 msec, 500-msec conditions were run for both rise times. (4) Both Os were naive.

Table 2
Results of Experiment II: Effects of Rise Time and Frequency on Detection and Recognition of Increments and Decrements in a Pure Tone

Frequency (Hz)	Rise Time (Msec)	Duration (Msec)	O CM				O WL			
			Increment Threshold (dB)	Decrement Threshold (dB)	Percent Correct in Recognition	Replication?	Increment Threshold (dB)	Decrement Threshold (dB)	Percent Correct in Recognition	Replication?
4000	1.0	50	-10.2	-10.7	76	x	-10.4	-9.5	58	
		100	-10.3	-9.9	70		-10.7	-10.7	61	
		300	-14.2	-13.3	76		-13.6	-11.4	89	
		500	-12.2	-12.0	98					
	10.0	50	-9.3	-10.1	72		-9.2	-7.8	63	
		100	-9.8	-10.2	74		-11.5	-9.9	55	
		300	-12.5	-11.5	96	x	-14.4	-11.9	79	
		500	-11.9	-11.3	84					
250	1.0	50	-6.8	-7.1	75		-9.2	-8.9	62	
		100	-7.5	-7.3	80	x	-9.9	-9.9	67	
		300	-8.7	-9.0	91	x	-8.5	-9.1	94	x
	10.0	50	-6.3	-7.1	66		-8.5	-8.8	68	
		100	-6.9	-7.9	70		-10.0	-9.5	74	x
		300	-9.6	-8.9	90		-10.6	-9.3	100	

Results and Discussion

Table 2 gives the results of the experiment. The detection-recognition disparity (recognition improving with duration as detection performance remains constant) occurs in all conditions, although C.M.'s 4,000-Hz 10-msec rise time data are noisy. There is no obvious effect of frequency. As in Experiment I, there is a tendency for the 50-msec signals to yield lower thresholds when the rise time is short ($p < .01$, two-tailed test).

Although there are hints in the data of these experiments that off-frequency listening may be taking place (e.g., the absence of the detection-recognition disparity for O.N.M. at the longest rise time in Experiment I, and the effects of rise time on threshold at short durations), it seems fair to conclude that off-frequency listening does not entirely account for the detection-recognition disparity in these experiments, since the extent of the effect is not generally related to the proportion of signal energy lying outside the critical band (or to any similar measure). The situation is not, however, clear-cut. The spectra of the signals in different conditions differ considerably; if an O is able to adjust an internal filter in response to these differences, his performance will depend heavily on how he makes this adjustment—there is no reason why he must behave optimally or always according to the same rule. A convincing demonstration that the detection-recognition disparity does not depend on off-frequency listening requires a situation in which the conditions allowing off-frequency listening are minimized. Such a situation is investigated in the next experiment.

EXPERIMENT III: INCREMENTS AND DECREMENTS IN A NOISE BACKGROUND

The optimal stimulus condition for testing the off-frequency listening explanation would have an identical signal-to-noise ratio at all points of the spectrum. This situation is approximated if the signals to be detected and recognized are increments and decrements in wideband noise. The spectra of the signals and of the masker will then be quite similar, and the location of the O's internal filter can have little effect on his performance, no matter what strategies he adopts.

Procedures

The procedures and Os used were the same as in Experiment II, with the following exceptions: Signals were increments and decrements in a continuous noise background with a total SPL of 62 dB, produced by a General Radio 1390-B noise generator and put through a Krohn-Hite 330M bandpass filter whose 3-dB cutoff points were 194 and 5,194 Hz. The filter had a nominal attenuation of 24 dB/octave. In the threshold estimation conditions, the intensity difference between adjacent levels was 3 dB.

Results and Discussion

The results are given in Table 3. There is no evidence for (and scant possibility of) off-frequency listening in these data, yet the detection-recognition disparity seems just as robust as with tones. For both Os and both rise times, recognition performance improves with duration in the usual way, detection performance being held constant.

Table 3
Results of Experiment III: Detection and Recognition of Increments and Decrements in Broad-Band Noise

O CM					O WL				
Rise Time (Msec)	Duration (Msec)	Increment Threshold (dB)	Decrement Threshold (dB)	Percent Correct in Recognition	Replication?	Increment Threshold (dB)	Decrement Threshold (dB)	Percent Correct in Recognition	Replication?
1.0	50	-7.0	-6.6	62		-7.5	-7.2	64	
	100	10.0	-8.1	65		-8.0	-7.7	77	
	300	9.8	-8.6	86	x	-10.7	-11.4	69	
	500					-10.3	-10.4	92	
10.0	50	8.2	-7.4	72		-7.0	-8.0	68	
	100	7.4	-7.5	82		-10.8	-8.5	74	
	300	-11.0	-9.8	90		-11.1	-10.1	84	
	500					-11.9	-9.1	96	

EXPERIMENT IV: TONAL INCREMENTS AND DECREMENTS IN THE PRESENCE OF NOISE

An aspect of these data that is, in principle, relevant to both change detection and off-frequency listening is the nature of the relation between increment (or decrement) threshold and duration. Macmillan (1971) and Leshowitz and Wightman (1972) both argue that shallow intensity-duration curves (i.e., little effect of increasing duration) must always occur in conjunction with the detection-recognition disparity. Table 4 gives the slopes, in decibels per log unit of duration, of the least-squares best-fitting lines through the threshold points for Experiments I-III. Unfortunately, strong conclusions cannot be drawn from these computations, for several reasons. There is considerable inter-O variability. Many of the curves whose "slopes" are given are noticeably nonlinear. Most seriously, it is hard to know how shallow the slopes would need to be to satisfy the prediction.

In this experiment, an attempt is made to manipulate the slope of the intensity-duration function in order to see whether the detection-recognition disparity will also be altered. The manipulation used is the addition of a "noise floor" to a tonal background and signals. Evidence that the addition of noise will increase the amount of temporal integration in this situation was found by Leshowitz and Wightman (1971). They observed a complete absence of temporal integration between 10 and 100 msec when signals were unfiltered increments in the intensity of a pure tone; however, when a continuous noise masker was added to the tone, the threshold for the 100-msec tone was lower than it was for the 10-msec tone.

Procedures

The experiments with noise were done at the same time and with the same Os as the study (without noise) reported as Experiment 3 in Macmillan (1971). The procedures are described in detail in that article. The main departures from the procedures

described for Experiments I-III are: (1) The tone had a frequency of 1,000 Hz and was presented at 56 dB SPL. (2) Signal rise times were fast. (3) Trials were not self-paced, but were presented to the O at a rate of one every 3 sec. (4) The time between the offset of a signal in the first interval and the onset of a signal in the second was approximately 400 msec. (5) Stimuli were presented binaurally through TDH-39 earphones. (6) The method for estimating the threshold intensity was less formal; thus, in this experiment, rather than all estimated threshold signals being assumed equally detectable,

Table 4
Slopes of Intensity-Duration Relations for Experiments I-IV

Experiment	Stimulus Condition	O	Rise Time (Msec)	Increment Slope (dB/Log Unit)	Decrement Slope (dB/Log Unit)
I	1000-Hz Tone	AB	0.5	-3.69	-3.59
			1.0	-4.28	-2.65
			5.0	-3.81	-2.45
		NM	0.5	-2.99	-2.49
			1.0	-4.02	-3.67
			5.0	-4.28	-3.95
II	4000-Hz Tone	CM	1.0	-5.42	-3.69
			10.0	-4.25	-1.88
		WL	1.0	-4.29	-2.35
	250-Hz Tone		10.0	-6.63	-5.17
		CM	1.0	-2.45	-2.54
			10.0	-4.37	-2.29
III	Noise	CM	1.0	+1.08	-0.08
			10.0	-2.57	-0.54
		WL	1.0	-3.23	-2.42
			10.0	-3.96	-3.24
			1.0	-4.25	-5.61
			10.0	-4.85	-2.76
IV	1000-Hz Tone	EB	0.0	-2.61	-2.24
		RZ	0.0	-2.41	-1.66
		KR	0.0	-2.82	-1.74
	1000-Hz Tone with Noise	EB	0.0	-6.00	-3.62
		RZ	0.0	-3.86	-2.59
		KR	0.0	-4.26	-2.44

Note—Slopes are for least-squares best linear fits; data from durations greater than 300 msec are not included.

Table 5
Results of Experiment IV: Effects of Noise Floor on Detection and Recognition of Increments and Decrements in a Pure Tone

Noise Floor	Duration (Msec)	Increment Detection (dB)	Decrement Detection (dB)	Percent Correct in Detection*	Percent Correct in Recognition
O EB					
No	15	-9.1	-8.7	73.5	60
	50	-9.1	-9.0	83.5	78
	100	-10.4	-9.3	76.0	78
	225	-12.2	-11.6	75.5	90
	600	-13.9	-15.3	77.5	91
Yes	15	-2.7	-3.9	75.0	74
	50	-6.8	-6.6	72.5	81
	100	-7.8	-5.8	74.0	77
	225	-9.9	-8.7	69.0	88
	600	-12.2	-10.1	71.5	90
O RZ					
No	15	-7.8	-7.0	73.0	72
	50	-9.9	-9.7	71.0	81
	100	-9.5	-8.4	83.0	78
	225	-10.9	-9.3	75.5	86
	600	-10.4	-9.7	70.5	93
Yes	15	-5.2	-5.1	71.0	57
	50	-7.3	-7.4	72.0	66
	100	-9.1	-7.9	66.5	67
	225	-9.5	-8.1	72.5	70
	600	-9.5	-9.3	70.0	95
O KR					
No	15	-7.8	-7.4	70.0	55
	50	-8.7	-8.4	77.0	62
	100	-10.4	-9.3	76.5	64
	225	-10.9	-9.3	78.0	77
	600	-10.9	-10.1	76.5	98
Yes	15	-5.2	-5.3	74.0	72
	50	-7.3	-7.9	74.5	73
	100	-8.1	-7.4	70.0	89
	225	-10.4	-8.4	70.0	73
	600	-9.5	-10.6	71.5	98

*Average of increment and decrement detection, rounded off to nearest 0.5.

detection performance was directly measured after the threshold was estimated.

The durations used were 15, 50, 100, 225, and 600 msec. The total SPL of the noise (which was not filtered) was 50 dB.

Results and Discussion

Table 5 gives the results of the experiment, both with and without noise background (the nonnoise data are summarized from Macmillan, 1971). The absolute levels of the thresholds are, of course, higher in the presence of noise.

Table 4 presents the slopes of the best-fitting intensity-duration functions, computed using only the shortest four durations.⁶ It can be seen that the average slopes increase (in absolute value) in the presence of noise (for increments from 2.61 to 4.71 dB per log unit

of duration). In fact, a difference in this direction occurs for all Os, for both increments and decrements.

In view of this revival of temporal integration in the presence of noise, the off-frequency listening hypothesis predicts a severe reduction in the detection-recognition disparity. This reduction does not occur. It is possible, of course, that the "off-frequency" energy was not entirely masked by the noise and that some off-frequency listening may still be occurring. What the data clearly show is that off-frequency listening is not the main explanation of the detection-recognition disparity. If it were, substantial changes in the slope of the intensity-duration function would be accompanied by substantial changes in the extent of the detection-recognition disparity.

EXPERIMENT V: UNCERTAIN INCREMENT-DECREMENT DETECTION IN THE PRESENCE OF NOISE

Macmillan (1971) offered evidence for change detection from a second type of experiment, the uncertain detection paradigm. If the signal presented in one of the two temporal forced-choice intervals may be, on any given trial, either an increment or a decrement, then a signal detection theory analysis which assumes that the sensory events resulting from decrements, no change, and increments in the background lie on a single decision axis predicts a decline in performance due to uncertainty. A change detector, on the other hand, should not show this decline, since it does not identify the signals in the first place. This leads to the prediction that the decline in performance due to uncertainty should be greatest at the longest signal durations, where the change detector contributes least to detection.

This phenomenon could be accounted for by the off-frequency listening hypothesis by assuming that the O tunes his filter off-frequency for short durations, but on-frequency for long durations. At short durations, there is considerable energy splatter, which is identical for increments and decrements: introducing uncertainty concerning the direction of the change will not change the energy spectrum off-frequency, and thus will not harm performance. At long durations, the O is tuned to the signal frequency, and Macmillan's (1971) signal detection theory analysis predicts a decline in performance when the direction of the change is uncertain.

The present experiment investigates whether duration still influences the relative detectability of certain and uncertain signals when a noise floor is present. Under these conditions, the off-frequency listening hypothesis predicts that the duration of the signal will not affect the relative certain-uncertain detectability. Rather, since the O is tuned to the signal frequency, uncertain detection should be uniformly poorer than certain detection. The change detection hypothesis, on the other hand, predicts that uncertain detection will decline

Table 6
Results of Experiment V: Percent Correct in Certain and Uncertain Detection of Increments and Decrements in a Pure Tone, With and Without a Noise Floor

Noise Floor?	Duration (Msec)	O LB			O RZ		
		Increment Detection	Decrement Detection	Uncertain Increment-Decrement Detection	Increment Detection	Decrement Detection	Uncertain Increment-Decrement Detection
No	15	74	74	66	79	71	70
	50	81	81	77	74	76	72
	100	86	79	77	74	70	75
	225	77	84	69	78	71	70
	600	72	74	59	84	74	58
Yes	15	73	71	67	77	75	69
	50	78	74	68	81	69	75
	100	73	73	67	82	72	68
	225	69	71	64	82	70	68
	600	72	71	57	74	66	55

with duration, relative to certain detection, whether or not a noise floor is present.

Procedures

The procedures followed were identical to those described in Experiment 4 of Macmillan (1971), which is the no-noise version of this experiment. The noise background and the signal durations were the same as in Experiment IV of the present report. Two of the three Os from Experiment IV completed the experiment.

Results and Discussion

The data are given in Table 6 for both the noise and no-noise conditions (the latter summarized from Macmillan, 1971). For both conditions, the decline due to uncertainty is large at the longest duration (600 msec) and small at the shortest four durations. At the short durations, the decline is only 4.8 percentage points for no noise background, 6.1 when noise is present; the difference between these two figures, although in the

Fig. 1. The detection-recognition disparity in Experiments I-IV. The difference between percent correct in increment-decrement recognition and mean percent correct in increment and decrement detection, averaged across Os, is plotted against signal duration. "Short" rise times are 0.5 and 1.0 msec; "long" rise times are 5.0 and 10.0 msec.

Fig. 2. Hypothesized neural firing rate as a function of time for increments and decrements.

direction predicted by the off-frequency listening hypothesis, is statistically insignificant and is, in fact, entirely due to the data at 100 msec. The conclusion is unavoidable that the effect of duration on the decline due to uncertainty, like the detection-recognition disparity, is not influenced by the addition of a noise background and, thus, cannot reasonably be attributed to off-frequency listening.

DISCUSSION

Figure 1 summarizes the main effect from the first four experiments. It shows the difference between percent correct in detection and recognition, averaged across Os, for all stimulus conditions investigated. (In Experiments I, II, and III, percent correct in detection is assumed to be 73.5%, the theoretical value estimated by the staircase procedure.) One way to estimate the size of the detection-recognition disparity is to find the slopes of the least-squares best-fitting lines to the various sets of points in Fig. 1. These turn out to be: for tones/no rise time, 18.0 percentage points per log unit of duration; for tones/short rise time, 18.2; for tones/long rise time, 6.4; for tones in noise background, 16.7; for noise, 25.2. Thus, except for the decline of the effect for pure tones with long rise times, there are no compelling differences across conditions. Possibly there is an increased effect with noise, but since this is predicted by no proposed model, the possibility is of little interest.

An acceptable account of these results should deal with at least four surprising aspects of the data: (1) increments are generally easier to detect than are decrements, (2) threshold increment intensity depends more heavily on duration than does threshold decrement intensity, (3) the detection-recognition disparity holds, and (4) uncertain increment-decrement detection depends on duration. A final result, previously reported (Macmillan, 1971), also restricts the possible explanations: (5) detectability of increments in a pure

tone is unaffected by randomizing their duration.

The model to be proposed is inspired by Luce and Green's (1972) neural timing theory, in which the decisions made by Os in psychophysical experiments are based on interarrival times (IATs) between successive neural pulses. Changes in stimulus intensity are assumed to lead to changes in the average (Poisson) rate at which the pulses arrive, and thus to changes in the distribution of IATs. This theory is motivated in part by physiological data on IATs; such data provide a convenient starting point for the present analysis.

Physiological data have not been obtained under stimulus conditions identical to those used in the present study. However, a good deal is known about responses to similar signals in the absence of a background (Kiang, 1965; Goldstein, Hall, & Butterfield, 1968; Moller, 1969). It is consistently found that turning on an auditory signal leads to a large increase in neural firing rate, which then declines as the signal continues. In the auditory nerve, the offset of the signal leads to a brief suppression of firing below the baseline rate (Kiang, 1965); in the cortex, cells have been found which are sensitive to onsets and offsets (Goldstein et al, 1968). A safe conclusion is that an increment in the intensity of an auditory background is not neurally reflected just as a change in firing rate for the duration of the increment. Rather, there are strong transient effects.

The exact nature of the transient information available to the O is, of course, not completely specified by these data, but the following is a simple possibility. Suppose all neural information relevant to the O's task in these experiments is carried on one neural channel, on which pulses are carried at a Poisson rate, the mean of which is determined by the stimulus waveform. Whenever the level of the background increases quickly, there is a sizable jump in the Poisson rate, declining over a short period to a stable rate higher than the initial one. Whenever the level of the background decreases quickly, there is a sizable drop in the firing rate, which then

increases over a short period to a stable rate lower than the initial one. Figure 2 shows schematically the effects produced by increments and decrements on Poisson rate under this hypothesis.

Now, if the O is using IATs as the basis for his decisions in these experiments, what should he do? Luce and Green (1972, p. 30) argue that neural events are sufficiently rare in detection experiments that few IATs are observed by the listener before a decision is made. It is clear from Fig. 2 that either very short or very long IATs might result from a signal of either type. Suppose the O collects the first K IATs in each interval, where K is fixed by the O's "memory capacity," and uses decision rules of the following type: In forced-choice detection, respond to the interval in which more long and short (rather than moderate) IATs are observed; in recognition, locate the increment in the interval with the higher ratio of short to long IATs. The criteria by which the O decides whether an IAT is fast, moderate, or slow may be reasonably supposed to be insensitive to duration; the value of K , the memory capacity (Luce & Green, 1972), also does not depend on duration. Thus, the O's strategy is consistent with the data from the randomized duration experiment (Macmillan, 1971, Experiment 5).

When the signal duration is short, larger proportions of the K intervals collected by the O will be both long and short if either an increment or a decrement is presented. This will lead to good detection performance but poor recognition performance. At longer durations, most of the observed IATs will come from the part of the signal interval in which the Poisson rate is stable, and good recognition as well as good detection will be possible. Thus, the detection-recognition disparity will occur. A similar argument accounts for the uncertain detection effect (Experiment 5).

If K is not too large and the signal duration is long, then an increment is more likely than is a decrement to fill the store before the observation interval ends; thus, increments will be more detectable than decrements. At short durations, where a stable firing rate is attained only briefly, this is not true, and increments and decrements will be approximately equally detectable; thus, the slope of the intensity-duration relation will be steeper for increments than for decrements. Thus, we see that a model of this sort can qualitatively account for all the phenomena listed above; I do not attempt here to determine values for the many parameters and fit the

resulting model quantitatively. The main point of this discussion is to indicate a direction one might take in devising models which satisfy the restrictions imposed by the data.

Temporal Integration

Macmillan (1971) argued that any two-process model which could account for the detection-recognition disparity must also predict a shallow intensity-duration relation. Yet, in the present study, the disparity was shown to be largely independent of the intensity-duration relation (see Table 7 and Fig. 1). The apparent contradiction arises from the ambiguity of the prediction: compared to what should the slope be shallow? The fact that the different stimulus situations used in this study yield different intensity-duration relations is not crucial, since the nature of this relation depends on many factors (among them, the usefulness of off-frequency listening).

What is true is that a model including two processes—change detection and integrative detection—predicts less temporal integration than does an otherwise identical model which is purely integrative. Thus, we could test the change detection hypothesis by looking for intensity-duration relations which are more shallow than those predicted by integrative models. For tonal stimuli, the predictions of existing models depend on a large number of assumptions concerning internal processing of the stimulus; there is no agreement on one predicted slope. The simple energy detector for noise signals (Green & Swets, 1966) predicts a slope of 5.0 dB per log unit, which is in fact slightly greater than the 4.1 and 3.5 found in Experiment III for increments and decrements, although less than some other estimates (e.g., Rochester, 1971). Of course, the estimated slope depends on the range of durations used, since the extent of integration apparently declines with increasing duration. The fact that the durations used in the present study were relatively long may help to account for the rather shallow intensity-duration relations observed.

CONCLUSIONS

The experiments reported here place a number of restrictions on models of auditory detection. Clearly, Os process the stimulus waveform in the time domain, and the information they extract from it is more complex

Table 7
Average Slopes of Intensity-Duration Relations

Stimulus Condition	Experiment	Number of Os	Number of Conditions	Durations (Msec)	Increment Slope (dB/Log Unit)	Decrement Slope (dB/Log Unit)
Tone, no rise time	4	3	3	15-225	-2.61	-1.88
Tone, short (0.5- or 1.0-msec) rise time	1,2	4	8	25-300	-3.26	-2.63
Tone, long (5.0- or 10.0-msec) rise time	1,2	4	6	25-300	-4.32	-2.71
Tone with noise floor	4	3	3	15-225	-4.71	-2.88
Noise	3	2	4	50-300	-4.07	-3.51

than is supposed by straightforward integrative models. The common assumption that the O reduces the information in a single observation interval to a single number (e.g., an energy estimate or a correlation coefficient) is too simple. On the other hand, the data do not merely show, as usual, that perception is more complicated than heretofore thought: they also indicate that many of the subtle abilities often attributed to Os (listening only for a period of time equal to the signal duration or setting a filter in optimal locations) should not, and need not, be assumed.

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NOTES

1. To find the power spectrum, we first compute the amplitude spectrum of the envelope, then multiply by the amplitude spectrum of the sine wave to give the amplitude spectrum of the tone burst (this is sketched in Wightman, 1971). For a signal whose envelope increases linearly for r sec. has a constant (unit) value for T sec, and decreases linearly to zero in r sec, this yields:

$$F(\omega) = \left(\frac{T+r}{2} \right) \left[\frac{\sin \frac{1}{2}(\omega - \omega_0)(T+r)}{\frac{1}{2}(\omega - \omega_0)(T+r)} \cdot \frac{\sin \frac{1}{2}(\omega - \omega_0)r}{\frac{1}{2}(\omega - \omega_0)r} \right. \\ \left. + \frac{\sin \frac{1}{2}(\omega + \omega_0)(T+r)}{\frac{1}{2}(\omega + \omega_0)(T+r)} \cdot \frac{\sin \frac{1}{2}(\omega + \omega_0)r}{\frac{1}{2}(\omega + \omega_0)r} \right]$$

The energy spectrum, $|F(\omega)|^2$, can now be found in a straightforward, if laborious, manner.

2. The calculations are based on the assumption that, in listening off-frequency, (1) the O is sensitive to those frequencies outside the "critical bandwidth" centered at the signal frequency, and (2) the bandwidth of the internal filter is uninfluenced by duration. The first assumption is too simple—the effective bandwidth of the internal filter clearly depends on task requirements (Penner, 1972). The second assumption is false—critical bandwidth apparently increases as duration decreases (Hamilton, 1957). However, only the reasonable assumption that the region of the spectrum which is off-frequency does not change with signal rise time is critical to the (qualitative) conclusion.

3. This procedure was adopted because the psychometric function for signals which are increments in a pure tone is sometimes found to be linear in $\Delta v/v$ (Stevens, Morgan, & Volkman, 1941; Larkin & Norman, 1964).

4. Theoretically, this is an estimate of the point on the psychometric function at which the O is making about 73.5% correct decisions. No direct check of this prediction was made; however, in similar experiments, it has been found that Os in fixed-signal-level experiments perform at a slightly (5% or less) poorer level than that calculated theoretically.

5. About half of the conditions in Experiment I were run twice, because the first set of data indicated that the O was not performing as well as he had during practice sessions. In these cases, only the second result is reported, and it is marked as a "replication"; replications tended to be necessary in those conditions with short signal durations. The percent correct in recognition was higher in the replication data than in the original (9 of 11 cases): the detection thresholds were lower (21 of 22 cases). Although performing replications in this manner is perhaps not the most elegant of procedures, it does not bias the results in favor of the present arguments. In fact, the procedure was used to insure that the detection-recognition disparity was

not an artifact of variability in estimated threshold. (In Experiments II and III, a smaller number of replications were run. In Experiment II, thresholds were higher in 7 of 12 cases; in Experiment III, thresholds were higher in 2 of 2 cases. Percent correct was higher in all cases.)

6. The slopes for the no-noise condition differ from those given for the same data in Macmillan (1971), where an

approximation was used [see Note 2 of Macmillan (1971)], and where all durations were included in the computation.

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