Attention and multidimensional discrimination¹

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Observers' ability to perform several discrimination tasks at the same time was tested using a two-alternative temporal forced-choice procedure. Discrimination of two auditory dimensions (pitch and intensity) and two visual dimensions (horizontal position and vertical position) was measured under conditions where one, two or all four dimensions required attention. Three signal durations were used: 67, 133, and 200 msec. Increasing the number of dimensions requiring attention systematically reduces the precisions of discrimination for each dimension. Auditory and visual discrimination is affected similarly. The amount of reduction in discrimination is independent of whether the dimensions requiring attention involve the same or different sensory modalities. The data are analyzed for evidence of a constant processing capacity employed in both single and multidimensional discrimination. The possibility that the observed performance levels could be achieved by sequentially processing the simultaneous inputs is also considered.

Until recently, most psychophysical experiments have studied sensory mechanisms involved in processing signals that vary along a single dimension. Under ordinary circumstances, however, the sensory system must operate in an environment where incoming signals vary along many different dimensions and often must deal with signals occurring simultaneously in different sensory modalities. In this report, we explore the question of how an O's performance on a set of simple discrimination tasks is affected by requiring the O to perform a number of these tasks at the same time.

The history of investigation into performance of simultaneous psychophysical tasks has been brief and rather uneventful. In a typical experiment, an O's performance on a detection (Loveless, 1957, 1959; Brown & Hopkins, 1967), discrimination (Eijkman & Vendrick, 1965) or a vigilance task (Bucker & McGrath, 1961) is measured first when auditory and visual signals are presented individually, then with both auditory and visual signals presented at the same time. Generally, the Os have been able to perform the auditory and visual tasks together as well as they could perform each of the tasks alone. The conclusion drawn from these studies has been unanimous: Os can apparently process information in two different sensory channels independently and simultaneously.

This conclusion is of interest since it contradicts a popular view of attention, the "single channel attention hypothesis" (Craik, 1948; Welford, 1952; Broadbent, 1958; Treisman, 1964; Moray, 1967). This hypothesis proposes that all sensory messages converge on one central processor which has a limited capacity for processing information. Whenever a number of different messages arrives at the central processor at the same time, the processor deals with each message, one at a time. Since simultaneous messages must form a queue to await service by the central mechanism, the information on some of the messages may be lost while others are being processed.

There have been several arguments used to reconcile the results of the psychophysical studies with the single channel attention hypothesis. One argument is that the sensory analysis of a psychophysical signal is a relatively primitive type of process, and because of the small processing capacity required, several discrimination tasks can be performed simultaneously. "It seems that analysis of simple physical signals precedes both the selective filter and the analysis of verbal content in the perceptual sequence, that the bottleneck in attention arises chiefly in speech recognition where of course the information load is usually much higher" (Treisman & Geffen, 1967). Numerous studies have demonstrated that Os have difficulty attending to more than one verbal message at a time (Mowbray, 1952, 1953, 1954, 1964; Poulton, 1953; Broadbent, 1958; Broadbent & Gregory, 1963; Treisman, 1964; Treisman & Geffen, 1967). It has also been argued that although

Os appear to be processing several signals simultaneously, in fact they may be sequentially attending to each signal. When a particular task does not require all the processing capacity, switching attention among the various signals would not be detected in the multitask performance data.

Both these arguments are based on inferences about the processing capacity required to perform various perceptual tasks, and are invulnerable to empirical tests without an explicit measure of that processing capacity. Before we can accept the single channel hypothesis, we must consider possible theoretical rationales for measuring the processing capacity involved in single and multitask situations and, from this, determine the quantitative behavior expected if a particular type of selective process underlies multitask performance.

In the present experiment, we examine performance in a multidimensional discrimination task under conditions where a measure of processing capacity can be derived and where the Os' performance might be assumed to be maximally sensitive to the operation of a single channel attention mechanism. The most important procedural departure from prior investigations is the use of brief signals. If an O has single channel attention mechanism which cannot be switched rapidly among the various signals, then the duration of the signals should have a critical effect on his ability to perform several discrimination tasks simultaneously. With long duration signals he could deal with a number of different signals by sequentially processing each signal. With very brief signals the O should have difficulty in attending to more than one signal on any given trial. On the other hand, if the Os can process the information associated with all signals independently and simultaneously, then we would expect the signal duration to have a comparatively small effect on his ability to perform simultaneous tasks.

In addition to the use of brief signals, we measure the accuracy of discrimination of the components of a bidimensional signal when the dimensions belong to the same sensory modality as well as when the dimensions belong to different modalities. Comparison of bidimensional discrimination within and between modalities should provide evidence as to the boundaries of any underlying selective process. Finally, we examine conditions where Os must attend to four dimensions of a bisensory signal. Performance in four-dimensional conditions provides needed data on whether the behavior pattern observed for bidimensional discrimination can be extrapolated to larger numbers of dimensions.

METHOD

The experiment was a two-alternative forced-choice discrimination task in which Os were required to attend to one, two or four dimensions of a multidimensional signal. The dimensions were the pitch of a pure tone (P), the intensity of the same tone (I), the horizontal position of a dot on a TV screen (H), and the vertical position of the same dot (V). Discrimination was tested in nine different experimental tasks: four unidimensional tasks, one for each of the four stimulus dimensions; four bidimensional tasks made up of four of the six possible combinations of pitch, intensity, horizontal and vertical; and one four-dimensional task. Of the bidimensional tasks, two involved discrimination of dimensions within the same modality (P-I and H-V) and two involved discrimination of dimensions in different sensory modalities (P-H and I-V). Performance on the nine tasks was tested at each of three stimulus durations (67 msec, 133 msec, and 200 msec) making a total of 27 experimental conditions.

Signal Parameters

On every trial, two stimuli were presented in rapid succession. A stimulus consisted of the simultaneous presentation of an auditory

and a visual signal each of which could vary in two dimensions. The O's task was to determine the relative values of the dimensions for the two stimulus presentations on a trial.

The auditory signal was a pure tone which could have one of two frequencies, 496 Hz or 500 Hz and one of two intensities, 58.6 dB or 60 dB (re 0002 dynes/cm²). An electronic switch turned the tone on and off at zero crossings of the sine wave signal. The signals were presented binaurally in a background of continuous white noise at 70 dB. Sharpe HA10 earphones were used with earmuffs that attenuated the room noise an average of 30 dB.

The visual signal was a dot approximately 1/2 in. in diameter. The dot was generated on an oscilloscope and transmitted via a closed circuit TV system to 17 in. TV monitors in the Os' booths. The dot could appear in one of four different positions describing a 1/4 in. square at the center of the TV screen. Depending on the task, the horizontal or vertical or both the horizontal and vertical position of the dot was changed between the two successive stimulus presentations on a trial.

A visual noise field produced by a white noise generator was maintained on the TV screen at all times. The signal to noise ratio and the ambient room lighting were set so that the Os had no difficulty in detecting the presence of the dot in the noise field. Video transmission was electronically interrupted at the termination of each signal presentation in order to erase the decaying image on the videocon. The interruption produced a post presentation flash which lasted for about 200 msec and which eliminated any persistence of the visual image. The TV monitor was viewed from a distance of about 6 ft. No bite board was provided.

To insure that the signal presentation continued for an integral number of TV frames, the presentation of the auditory and visual signals was synchronized to the vertical retrace blanking pulse of the TV camera. Because of the synchronization, the signal durations used were multiples of the frame rate of the TV camera: 16-2/3 msec.

When a dimension was to be discriminated, the values for that dimension were changed between the two stimulus presentations on a trial. The order of occurrence of the two values for a dimension was varied randomly from trial to trial. Dimensions which did not require discrimination maintained a constant value within a trial, the particular value being randomly determined before each trial.

The signals were presented for durations of 66 msec, 133 msec and 200 msec. The intersignal interval was 500 msec and the average time for a complete trial including response recording was about 5 sec. The signal generation system, trial by trial randomization and the operation of the response recording system were controlled automatically by equipment designed and constructed at Defense Research Establishment, Toronto.³

Procedure

Six Air Force housewives with normal vision and hearing served as Os in the experiment. All Os had participated in a three-week training period prior to the present experiment and were thoroughly familiar with the equipment and the experimental procedure. The Os were tested daily at the same time in individual experimental booths.

An O reported her discrimination of a dimension by indicating whether the first or the second stimuli presented on a trial had a particular value. For the two auditory tasks, the O reported which signal had the higher pitch and which signal was louder. For vertical and horizontal discrimination, the O reported which signal appeared in the upper position on the TV screen and the leftmost position respectively. The Os reported their responses by means of four pairs of push buttons, one pair for each dimension.

In order to minimize the possibility of memory and response interference in the multidimensional tasks, the Os were required to report their discrimination of only one dimension on a trial regardless of the number of dimensions attended to. The dimension reported was randomly determined after the stimulus presentation on a trial, with the restriction that Os were never required to report on a dimension not originally specified for attention. A set of pilot lights on the O's response panel informed

the Os as to the dimensions requiring attention, the dimension requiring a response and provided feedback as to the correct answer on every trial.

The various experimental conditions were tested in 50 trial runs during which the dimensions requiring discrimination and the signal duration were constant. One replication of 50 responses per O for each of the 27 experimental conditions was obtained every two days. The order in which the various conditions were tested was randomized within each two day block. A total of 18 replications was conducted which produced 900 responses per O for each of the 12 unidimensional conditions and approximately 450 responses per dimension for each O in each of the 15 bidimensional and four-dimensional tasks.

RESULTS

Before combining the responses over the 18 replications, an analysis of variance was performed on the unidimensional performance of each O. The analysis showed a nonsignificant Day effect with an average error variation of about twice the theoretical binominal variance. A graphic comparison of day to day performance on the multichannel tasks showed no practice effects.

The 27 experimental conditions yielded a total of 48 measures of per cent correct for each O: 12 for the unidimensional tasks, 24 for the bidimensional tasks, and 12 for the four-dimensional tasks. Since the discussion of the data requires a consideration of detectability statistics, the percent correct measures were converted to d' scores using the two-alternative forced-choice tables of Elliott (1964, p. 682-683). The group trends were found to be typical of the performance of individual Os and therefore the average performance of the six Os is reported.

Table 1 shows the mean d' for each dimension when one, two and four channels (dimensions) require attention. The average d' per channel decreases consistently from one-channel ($d' = 1.35$) to two-channel ($d' = .84$) to four-channel tasks ($d' = .62$). The individual rows show the same trend for all dimensions and durations, there being no reversals in the table. The columns in Table 1 show that the accuracy of discrimination also depends on the duration of the signal with the effect being somewhat larger in single channel tasks than in multichannel tasks.

Figure 1 shows d' per channel as a function of the number of input channels separately for the visual and auditory modalities. Performance on the pitch and intensity dimensions has been averaged across all conditions that involved the same number of input channels. A similar average was computed for the horizontal and vertical dimensions. Figure 1 shows a similar level of visual

Table 1
Measures of Detectability (d') for Four Dimensions
at Three Signal Durations and Four Input Conditions

Dimension	Signal Duration	Number of Input Channels			
		One Channel	Two Channels Within Modality	Two Channels Between Modality	Four Channels
Pitch	67 msec	.94	.74	.72	.65
	133 msec	1.49	.86	.98	.66
	200 msec	1.46	.89	1.06	.80
Intensity	67 msec	1.09	.60	.51	.33
	133 msec	1.42	.79	.78	.50
	200 msec	1.57	.89	.82	.53
Horizontal	67 msec	.78	.58	.56	.39
	133 msec	1.32	.77	.98	.61
	200 msec	1.47	.88	.95	.79
Vertical	67 msec	1.12	.86	.64	.45
	133 msec	1.66	1.03	.95	.79
	200 msec	1.87	1.26	1.12	.91
Mean	67 msec	.98	.69	.61	.46
	133 msec	1.47	.86	.92	.64
	200 msec	1.59	.98	.99	.76
Mean		1.35	.84	.84	.62

Fig. 1. Mean detectability (d') per channel as a function of number of input channels for auditory and visual modalities. Average data from six Os.

and auditory discrimination of unidimensional signals, a result which is due to the initial selection of signal parameters. The striking feature in Fig. 1 is that an increase in the number of channels being monitored reduces the precision of both the visual and auditory discrimination by the same amount. The operations associated with processing information in the different modalities are apparently affected equally by changes in the number of dimensions requiring attention.

Multidimensional discrimination also seems to be independent of whether the channels requiring attention involve the same or different sensory modalities. Table 1 shows that the average d' per dimension for two dimensions within the same modality equals the average d' per dimension for two dimensions in different sensory modalities ($d' = .84$). In Fig. 2, d' has been plotted as a function of signal duration for the single channel tasks, the two-channel within modality tasks (P-I, H-V), the two-channel between modality tasks (P-H, I-V) and the four-channel tasks. The two panels show auditory and visual performance separately. Each data point in Fig. 2 represents an average of the performance on the two dimensions associated with the same modality. For example, the points shown for the auditory dimensions within a modality represent an average d' for pitch and for intensity obtained in the P-I conditions at a particular signal duration. The points shown for between modalities represent an average of the d' for pitch in the P-H condition and the d' for intensity in the I-V condition. There is no systematic difference between performance on within modality tasks and performance on between modality tasks at any of the three signal durations. The pattern is similar for both vision and audition.

DISCUSSION

For the signal durations used in this experiment, discrimination processes operating on a given input dimension interfere with the processing of information on a different dimension. The amount of interference seems to be largely independent of the particular combination of dimensions being processed and the sensory modality involved, findings which are compatible with the notion of a central attention mechanism operating with a limited processing capacity. Before we consider the quantitative behavior of a single channel process, however, let us consider a method for assessing the relative processing capacity being employed in the single and multidimensional tasks.

Multidimensional Discrimination and Processing Capacity

According to modern detection theory (Green & Swets, 1966), the response of the sensory system to a given input signal can be treated as a sample statistic, whose probability distribution across trials depends on statistical fluctuations in the external signal and internal noise added during the processing of the signal. The precision of discrimination between two signals depends on the separation of the two probability distributions associated with the signals. By assuming the distributions are normal and have equal variance, the separation of their means can be scaled in terms of their common standard deviation, the detectability, d' , of signal detection theory.

This conception of the discrimination mechanism for individual stimulus dimensions as a statistical decision process, suggests a plausible way of determining the processing capacity of a multichannel processor. Consider a system which must monitor a number of different signal channels and which has an upper limit on the total rate at which it can sample the information in all channels. When only one channel is monitored, the full sampling capacity is applied to that channel. When more than one channel is monitored, the sampling capacity is divided among all active channels. The division of capacity forces a reduction in the average number of observations that can be taken on any particular signal before a decision about that signal is made.

Statistical theory relates the number of independent observations used in computing a sample statistic to the variability of that statistic: a reduction in the number of observations per sample produces a proportionate increase in the variance of the sample statistic computed in a trial. Since d' is scaled in standard deviation units, we would expect $(d')^2$ measured on a given channel to vary directly with the number of independent samples taken during the reception of the signal.

The precision of discrimination however, depends not only on the number of samples taken on an incoming signal, but also the amount of information contained in each sample point. Consequently, the discrimination of a particular signal under multichannel conditions, $(d'_M)^2$, will depend on the level of discrimination, $(d'_S)^2$, which can be obtained when the full sampling capacity, R , is applied to that signal under single channel conditions and the sampling capacity, r , which can be applied to the same signal under multichannel conditions:

$$(d'_M)^2 = (d'_S)^2 \frac{r}{R}$$

The ratio of $(d')^2$ for a particular channel under multichannel conditions to $(d')^2$ for the same channel under single channel conditions represents the proportion of single channel capacity maintained on a signal when several signals are processed at the same time. We call this measure the multichannel processing capacity (MPC).⁴

The value of MPC could vary between 0 representing chance

Fig. 2. Mean detectability per channel as a function of signal duration for auditory and visual modalities. Each curve is the average performance on two dimensions associated with the same modality. Parameter is the number of input channels. Average data from six Os.

performance ($r = 0$) and 1 indicating no change between single and multichannel performance ($r = R$). If we add up the MPC values obtained for each channel under multichannel conditions, then the total, MPC_T , could vary between 0 and N , the number of channels being monitored.

$$MPC_T = \frac{1}{R} \sum_{i=1}^N r_i$$

MPC_T should be 1 if the total capacity for all channels under multichannel conditions exactly equals the capacity applied to one channel under single channel conditions, our definition of a constant processing capacity. Values of the MPC_T less than 1 indicate the multichannel capacity is less than the single channel capacity. A MPC_T value of N represents the performance expected from a system which can process the information in all signal channels with the same precision in multichannel conditions as in single channel conditions.

Table 2 shows the MPC measures for the data obtained in this experiment. The values are computed by first squaring the d' obtained in single and multichannel conditions (Table 1) then taking the ratio of the $(d')^2$ for an individual channel under multichannel conditions to the $(d')^2$ for the same channel under single channel conditions. Column MPC_T shows the total MPC for each task.

For most of the tasks, MPC_T is less than 1. MPC_T for P-H and the P-I-H-V tasks come closest to 1 and MPC_T for the shortest signal duration (66 msec) is somewhat higher than for the two longer durations. With few exceptions, the MPC for individual channels is roughly equal, indicating that an equal proportion of the available capacity is applied to each channel. Apparently the Os in this experiment do not give preferential treatment to a particular channel under multichannel conditions. Pitch discrimination seems to be an exception to this rule in the P-I, 66 msec, and the P-I-H-V, 66 msec conditions. The other seven tasks involving pitch discrimination, however, do not show this trend. On the average, the total capacity applied to multichannel tasks appears to be about 85% of the single channel capacity.

We conclude that the Os in this experiment behave as if they are operating with a constant processing capacity which can be applied to one channel or divided among a number of channels although the division of capacity is not accomplished without some cost. The analysis of processing capacity, however, has not dealt explicitly with the question of whether the information in the different signal channels is processed simultaneously or successively under multichannel conditions. Let us turn now to an examination of the behavior expected from a single channel attention mechanism for which we require a somewhat different set of assumptions.

Sequential Attention to Simultaneous Inputs

Suppose the central processor is restricted to processing the information in only one signal channel at a time. One version of this mechanism would be that, on any given trial, the processor can deal with the information in only one signal channel, regardless of the number of channels requiring attention. The implication here is that switches of attention are not possible with the short duration signals used in this experiment. This would be

consistent with the view of a number of investigators (Cherry & Taylor, 1954; Broadbent, 1958; Kristofferson, 1965) who propose that a relatively large amount of time (50 - 200 msec) is required to switch attention among channels.

Given the limitation of attending to only one channel on a trial, the strategy which maximizes the average performance per channel is to attend to the same dimension on every trial, the dimension which is easiest to discriminate. Under multichannel conditions, performance on the selected dimension would be the same as for single channel conditions while performance on the neglected channels would drop to chance levels ($d' = 0$).

It is obvious from Table 1 that the Os do not use this strategy. Moreover, the MPC measures in Table 2 indicate that, on the contrary, the performance levels maintained on the various channels under multichannel conditions are roughly equal proportions of the single channel levels. An analysis of the individual Os' data shows the same pattern of results. None of the Os showed any tendency to consistently monitor a particular dimension to the exclusion of the other dimensions requiring attention.

Alternatively, we might assume that, rather than consistently select the same dimension on every trial, the Os distribute their attention equally among the dimensions by varying their choices from trial to trial. In two channel tasks, there is only a 50% chance that the channel selected for attention will also be selected for response. Average performance per channel under two-channel conditions at a specified duration therefore would be 50% of the average single channel performance at the same duration. Similarly, average four-channel performance would be 25% of the average single channel level.⁵ When we apply this rule to the data in Table 1, we see that, in 35 of the 36 possible comparisons, the observed performance level exceeds that which could be obtained if only one signal channel, randomly selected, is attended to on each trial. Under four-channel conditions at the shortest signal duration, the observed performance ($d' = .46$) is almost twice the expected level ($d' = .24$). Again, the analysis of the individual Os' data supports the same conclusion.

Since a slow switching attention process cannot account for the performance levels achieved in a multidimensional discrimination task, let us consider the behavior of a single channel mechanism which can be switched rapidly among the different input channels. During each signal presentation, it spends only part of the time operating on the information in a given channel, then switches to others. For this system, an increase in the number of channels requiring attention reduces the average time available for analyzing the information in each channel. Since, if the processor is not attending to a channel, its signal is not being analyzed and might just as well be absent, increasing the number of channels requiring attention is equivalent to reducing the signal duration on each channel.

On the bases of the data in Table 2, let us assume the Os tend to allocate an equal amount of time to each channel. Under this assumption, doubling the number of input channels should have the same effect on performance as reducing each signal duration by a half. In the present study (cf., Table 1) the average performance per channel under two-channel 133 msec conditions ($d' = .89$), should be the same as the average single channel performance with 66 msec signals ($d' = .98$). Similarly, the average

Table 2
Multichannel Processing Capacity

Signal Duration	Task																	
	P-I			H-V			P-H			I-V			Mean	P-I-H-V				
	P	I	MSI _T	H	V	MSI _T	P	H	MSI _T	I	V	MSI _T	MSI _T	P	I	H	V	MSI _T
66 msec	.62	.30	.92	.55	.59	1.14	.59	.51	1.10	.22	.33	.55	.93	.48	.09	.25	.16	.98
133 msec	.33	.31	.64	.34	.38	.72	.43	.55	.98	.30	.33	.63	.74	.20	.12	.21	.22	.75
200 msec	.37	.32	.69	.36	.46	.82	.53	.42	.95	.27	.36	.63	.77	.30	.11	.29	.24	.94
Mean	.44	.31	.75	.42	.47	.89	.52	.49	1.01	.26	.34	.60	.81	.33	.11	.25	.20	.89

Each table entry is the ratio of $(d')^2$ for the specified dimension under multichannel conditions to $(d')^2$ for the same dimension under single channel conditions. Average data from six observers.

four-channel performance with 133 msec signals ($d' = .64$) should be equal to two-channel performance with 66 msec signals ($d' = .65$). The Os' multichannel discrimination performance appears on the average to be equal to or slightly less than that which would be expected from a single channel process which can switch rapidly and which divides the processing time equally among the channels. Note also that the relative impairment under four-channel conditions where three switches of attention may be required is, if anything, slightly less than that observed for two-channel conditions where only one switch of attention would be needed. This trend is opposite to what would be predicted if any appreciable amount of time is lost during attention switches between channels.

An analysis of the multidimensional discrimination data in this experiment indicates that if the Os are sequentially processing simultaneous signals, they must be able to switch their attention rapidly and efficiently among the signals. The difficulty in arguing that a fast switching single-channel processor could account for the observed performance, however, is that its quantitative behavior becomes indistinguishable from a variety of equally plausible mechanisms for multichannel processing. A similar performance pattern, for example, would be obtained with a data sampling system where the information in all channels is sampled simultaneously but the sampling rate per channel is determined by the number of channels being monitored. Although different machinery might be needed to implement the sequential and simultaneous mode of operation, both mechanisms would result in a reduction of the average number of observations taken on a particular signal and, as a consequence, reduce $(d')^2$ correspondingly.

Signal detection theory gives us some assistance in this dilemma. It provides the analytic tool for quantifying, in statistical terms, the amount of interference arising in multichannel tasks. Thus we can to some extent separate the question of limitations in processing capacity from issues involving the detailed operation of the underlying system. The success of the theory in dealing with the discrimination of individual dimensions makes it an attractive starting point for a consideration of multidimensional signal processing.

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NOTES

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2. Address: Department of Psychology, University of California, San Diego, La Jolla, Calif. 92037.
3. For a more complete description of the equipment used in this study, see Forbes and Taylor (1967) and Lindsay (1966).
4. In a previous paper, we pointed out the relationship between the amount of information which can be extracted from a signal and the d' measure (Taylor, Lindsay, & Forbes, 1967). The derivation required the assumption of a coherent detector: the signal known exactly case of signal detection theory. The basic assumption of the present analysis is that, whatever the exact nature of the measure being computed on an incoming signal at a given moment, the measures are accumulated and averaged and the resulting statistic is normally distributed. Given these assumptions, which might reasonably be expected to apply to a wide variety of situations, the ratio of $(d')^2$ will reflect changes in the amount of information accumulated about a signal even though the absolute level of d' will depend on the particular type of detector operating.
5. Though strictly speaking the percentages should be computed on the response probability rather than on the d' statistic, the difference between the two computations is very small for the range of performance under consideration and does not affect the conclusions.

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