PRIOR ENTRY REEXAMINED: EFFECT OF ATTENTIONAL BIAS ON ORDER PERCEPTION*

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ABSTRACT

Perceived temporal order of two events in different sensory modalities depends on attentional bias toward one modality. The bias was induced and measured by a concurrent reaction-time task. The relation between stimulus intensity and the size of the "prior-entry" effect provides evidence about which stage of processing is influenced by attention.

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How do we perceive the time order of stimuli in two modalities? It was perhaps in relation to this question that selective attention was first invoked as an explanation in experimental psychology. In one of his seven laws of attention published in 1908, Titchener summarized several decades of experiments on this problem in his Law of Prior Entry (1908, p. 251). He asserted that "The stimulus for which we are predisposed requires less time than a like stimulus, for which we are unprepared, to produce its full conscious effect." The relation of this law to the perception of order depends on two important ideas. First, perceived order reflects the outcome of a race between perceptual processes in the two sensory channels. Second, the distribution of the observer's attentional bias between the two channels influences the speed of these processes.[1]

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[1]The relevant experiments in the 19th century were called <u>complication experiments</u>, a "complication" denoting a pair of stimuli from different modalities. These experiments were modeled after the astronomers' problem of determining when a star crossed a hairline (visual) in relation to a series of clicks (auditory). The differences among the points of subjective simultaneity of different observers, embodied in the idea of the "personal equation", were attributed in part to differences among their attentional biases toward the two sensory channels. (See Sanford, 1888.)

Shortly after Titchener published his law, Dunlap (1910) reconsidered the experiments on which it was based. He concluded that the effects claimed for attention were actually artifacts resulting from flaws in experimental method.[2]

In recent years, despite the revival of interest in both selective attention and perceptual latency, the validity of the law of prior entry has not been reconsidered.[3] Does attentional bias influence the latencies of the internal events people use to judge the order of stimuli, or their simultaneity? The question is important for at least two reasons. First, judgments of order and simultaneity are frequently used to study various aspects of information processing, ranging from the dependence of sensory latency on stimulus intensity (e.g., Roufs, 1963), to the comprehension of sentences (e.g., Ladefoged & Broadbent, 1960; Reber & Anderson, 1970). In almost none of these applications is any effort made to hold constant the observer's attentional bias. The existence of prior-

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[2]Most complication experiments involved multiple observations of a continuously rotating pointer and a discrete acoustic stimulus, with the observer judging the position the pointer assumed at the moment of the sound stimulus. Dunlap argued that the effects attributed to attention resulted from variations in the eye movements associated with the moving pointer, and he found fault with the use of multiple presentations before each judgment.

[3]See, e.g., Moray, 1969; Treisman, 1969; Broadbent, 1971. One reason for the neglect of prior entry may be semantic: theorists have used the terms "selective" and "divided" attention often, "biased" attention seldom. Order perception has been considered in relation to the switching of selective attention in the important work of A. B. Kristofferson (1963, 1967), but not in connection with the problem of prior entry.

entry effects would raise questions about the interpretation of such studies.

Secondly, if there is a prior-entry effect, then an understanding of the effect will shed light not only on how judgments of temporal order are accomplished, but also on the nature of attentional selectivity.

Our paper has two purposes. Using modern methods, we demonstrate the existence of prior-entry effects in two different pairs of sensory channels - an auditory-cutaneous pair and an auditory-visual pair. This leads to a more precise description of the effect than was available in the 19th century. In addition, we show how a study of the effect can discriminate between two models of attentional selectivity, and describe results that point tentatively to one of them.

Our experiments are in fact similar to one study that did avoid many of the early pitfalls. It was reported 45 years ago in a brief note by Sybil Stone (1926), and described by her as a preliminary experiment. Nonetheless it provides a characterization of the effect that our experiments confirm. Figure 1 shows an idealization of her results. One stimulus was <u>cutaneous</u> - a tap on the finger. The other was <u>auditory</u> - a click. Subjects

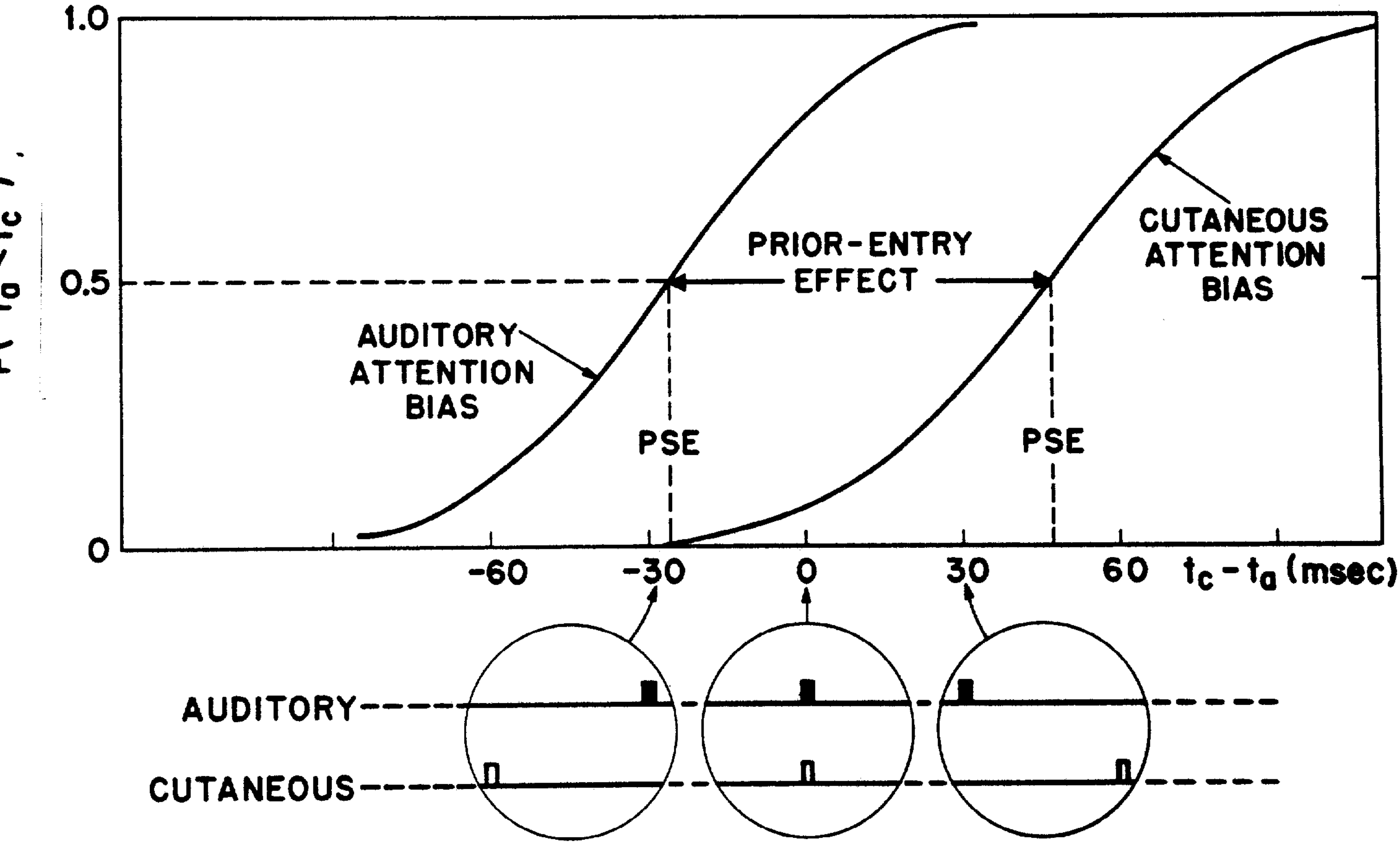

Figure 1

reported which of the two stimuli seemed to occur first.[4]

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[4]Stone used auditory and cutaneous channels to avoid the eye-movement problem that had been brought out by Dunlap (1910), and each judgment in her experiment was based on only a single presentation of the stimulus pair, avoiding problems associated with the multiple-look design. Subjects were permitted three response categories [auditory first ("$t_a < t_c$"), simultaneous ("$t_a = t_c$"), and cutaneous first]; for the data that Stone collected, which are presented in App. 1 and idealized in Fig. 1, we have approximated the two-category psychometric function by the quantity P("$t_a < t_c$") + P("$t_a = t_c$")/2. Asynchronies of the stimuli in Stone's experiment were varied according to the method of constant stimuli. Because of range effects and other problems (e.g., see Erlebacher & Sekuler, 1971), this method may not be ideal for determining the point of subjective simultaneity.

The ordinate shows the probability of reporting the auditory stimulus as first. As we move from left to right along the abscissa, the cutaneous stimulus becomes more delayed relative to the auditory stimulus. In different series of trials, subjects made these judgments under two attentional conditions. In one condition, which generated the lefthand psychometric function, they were asked to attend to the click. In the other condition, which generated the righthand function, they were asked to attend to the finger tap.[5] The prior-entry effect is revealed by the horizontal displacement of the functions obtained in the two attentional conditions. With attention biased toward the tap rather than the click, the tap must be more delayed for the click to be perceived first.

The 50%-point of the psychometric function is taken as the point of simultaneity in that condition, and the difference between the two 50%-points is a measure of the prior-entry effect. In this example the two 50%-points are -26 msec. and +47 msec., giving a prior-entry effect of 73 msec. Stone's subjects (see App. 1) produced an average effect of about 50 msec.[6]

Unlike previous workers, in our experiments we tried to control the attentional bias by something other than instructions, and we measured our success by something

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[5] We consider the use of instructions alone to control attention not to be ideal, since neither subject nor experimenter has an independent criterion for determining whether the instructions are being followed.

[6] Note that the existence of a prior-entry effect does not require that the entire psychometric function be horizontally displaced; alternatively, attention could influence the middle portion of the function more than the extremes, so that the two functions would have different shapes. Which of these forms the effect takes limits the theories that might account for it.

other than the prior-entry effect itself. To do this we combined judgments of order with a reaction-time task in which subjects reacted to one of the two stimuli. Figure 2 shows the two kinds of trials during the type of session

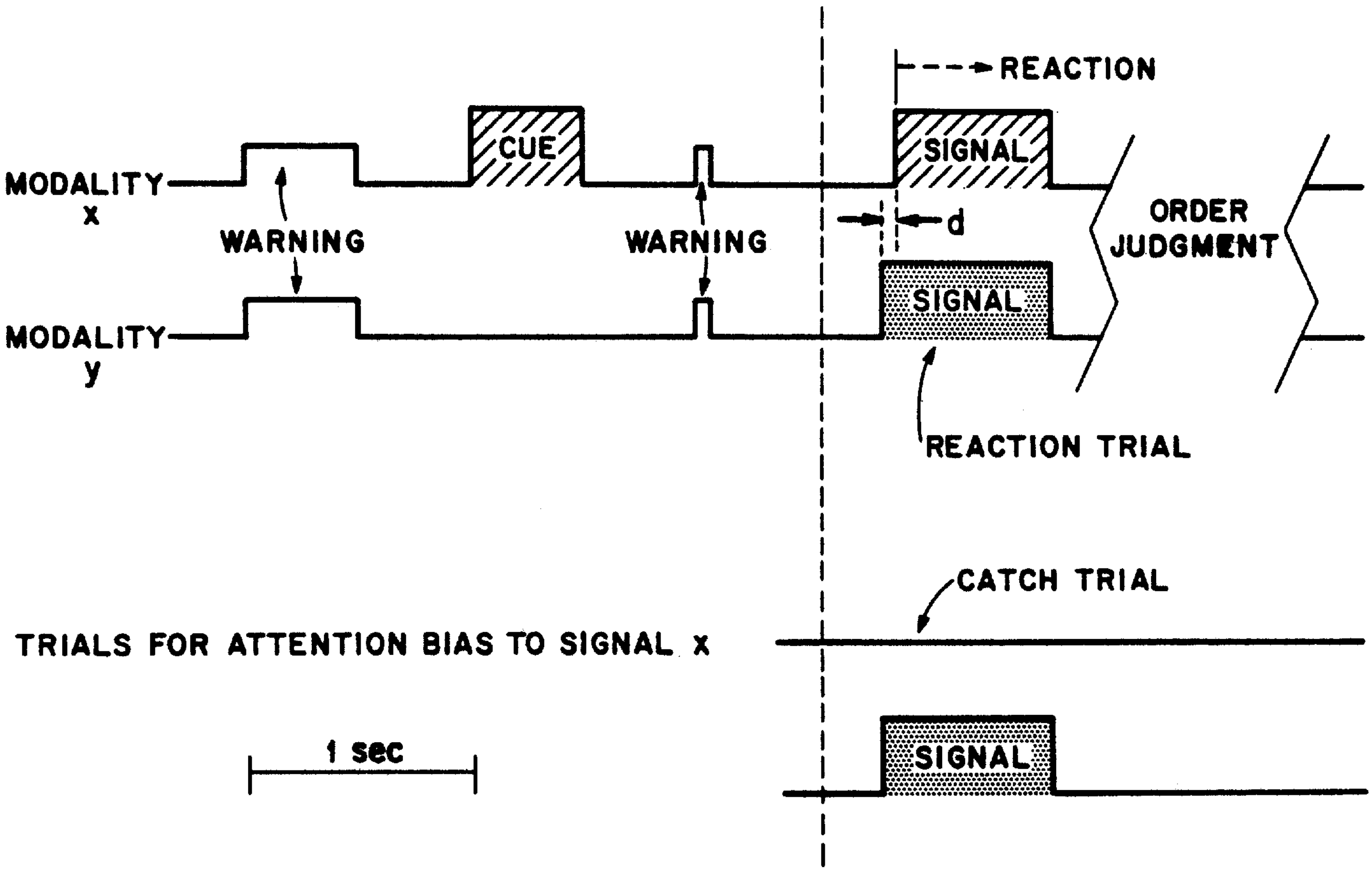

Figure 2

in which we tried to bias the attention toward modality x. A random half of the trials were reaction trials, requiring both a reaction and an order judgment, and the other half were catch trials, requiring no response. Both kinds of trials began with the bimodal warning signal. There followed a cue that was similar to the reaction signal, to remind the subject that he was reacting to signal x during that session, and then another warning signal. On a catch trial, shown at the bottom of the figure, this was followed by signal y only; these trials were included to insure that the reaction was selective, and reactions to signal y by itself were heavily penalized. On a reaction trial, shown at the top of the figure, both signals occurred, with a positive or negative time interval of d msec. between their onsets. The subject pulled a lever as quickly as he could after the channel x signal, and then pressed a key to indicate which signal seemed to start first.[7,8,9]

To vary the interval, d, between signal onsets, we used an up-and-down staircase procedure, which automatically centers the stimulus distribution at the point of simultaneity. In fact, we used four randomly interleaved staircases to reduce the predictability of the

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[7]Note that the events whose order was being judged in our experiments were signal onsets rather than pulses.

[8]Subjects also rated their degree of confidence on a three-point scale; the analysis of the ratings is excluded from the present report, however.

[9]Use of a fixed reaction signal for an entire session and a cue on each trial that provides (approximate) preview of that signal is similar to a practice felt desirable for reducing signal uncertainty and stabilizing performance in detection experiments (Green & Swets, 1966, pp. 394-395). For discussion of possible advantages of this method in reaction-time experiments, see LaBerge, 1971, p. 334.

stimulus sequence, and they were started at widely dispersed values of d.[10]

We have run two principal control procedures in these experiments. In the reaction-time control, subjects made no order judgments. In the experimental condition they were expected to maintain the same reaction-time performance as they could achieve in this control condition; deadlines were established and subjects rewarded accordingly. Insofar as they succeeded, we took this as evidence of the desired attentional bias. Our assumption here is that unless the bias is maintained, reaction-time performance will suffer.[11] We find that subjects are able to

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[10] Each run started with two randomly interleaved staircases, with step sizes of 40 msec. and standard widely separated starting points. After a criterion of convergence was met, four staircases with a 20-msec. step size were begun, with starting points distributed about the stimultaneity point that had been estimated from the initial pair of staircases. The step values associated with two of these staircases were a half-step away from the step values associated with the other two (stimuli thereby being presented with d-values 10 msec. apart), to increase precision and reduce bias. A change in the d-value of a staircase was permitted to occur in response to an order judgment only on those trials on which the reaction time did not exceed an adjustable deadline; deadlines were adjusted individually to permit d-value changes on about 75% of the trials. Each of the four staircases provided a single estimate of the simultaneity point, given by a mean of its mid-run estimates (see Levitt, 1970, and references therein). Standard errors of the mean of these four values were based on between-staircase variation.

Although subjects were informed regularly about their reaction-time performance, they were told nothing about the simultaneity points they generated until experiments were completed.

[11] The present method of controlling attention (by requiring a rapid detection response to one of the two stimuli in an order-judgment task) has similar aims as, but should not be confused with the LaBerge et al (1970) method (of unbalancing the stimulus probabilities in a discrimination choice-reaction task). It is an open question whether the same "attention" is controlled by the two methods. Insofar as it is the same or similar, however, our assumption is supported by the findings of LaBerge et al.

maintain this performance almost perfectly when order judgments are added. The second control, involving order-judgments only, showed that the reaction-time task did not reduce the precision of the order judgments.[12]

In the first experiment we shall report, the modalities were auditory and cutaneous. The auditory signal was a band-limited white noise delivered binaurally at 45 dB above threshold. The cutaneous signal was a train of electrical pulses delivered through two electrodes to the left forearm, at an intensity that produced a painless tingling sensation.[13] Attention was biased toward one signal for an entire session, and six sessions were run with each of six subjects.[14]

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[12] This finding helped to allay our concern that introducing a concurrent reaction-time task in the order-judgment experiment might, in addition to possibly influencing the point of subjective simultaneity, also interfere more generally with the order judgments and thereby increase their variability.

[13] We used constant-current 0.1-msec. pulses at a frequency of 50 Hz; a comfortable sensation level was produced by a current at twice the absolute threshold for a single pulse.

[14] Each pair of sessions contained one in which signal x of Fig. 2 was cutaneous, and another in which it was auditory, permitting the prior-entry effect to be estimated separately for each third of the experiment. The size of the mean effect grew from 45 to 65 msec., but this change was not significant. This led us to average the data over the three session pairs for each subject.

In Fig. 3 the mean prior-entry effect is represented separately for each subject. The 95% intervals,

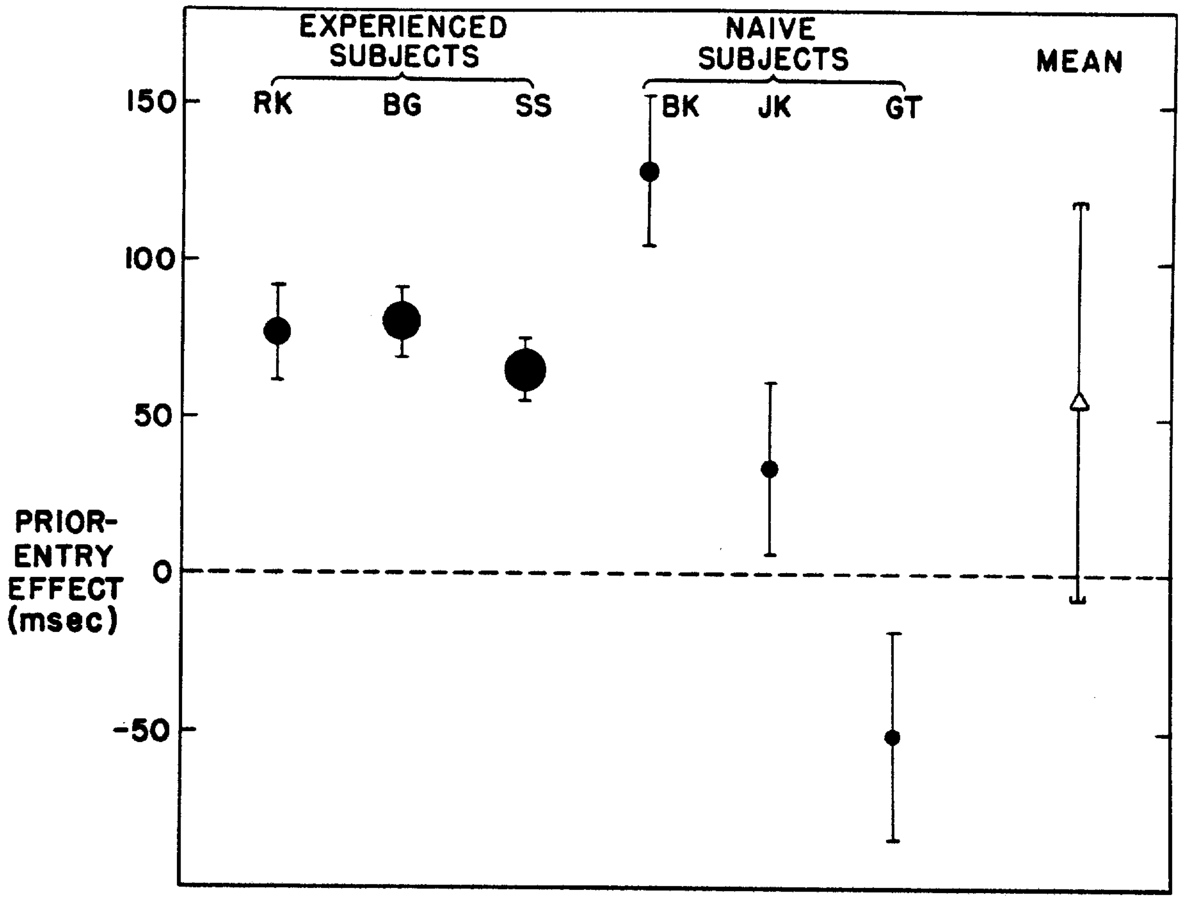

Figure 3

shown by the vertical lines, are based on within-subject variability. The sizes of the circles are proportional to the <u>reliability</u> of the estimates. We have done this to indicate how much weight should be given to each subject's data. The figure shows that subjects vary considerably in the stability of their order-judgments, and in the size of their prior-entry effect. The three subjects who were relatively experienced at making order judgments were far more stable than the three subjects who were relatively naive. Indeed, subject GT, on the far right, shows a reversed effect. This subject's reaction-time performance was also atypical, possibly suggesting an unusual strategy for dealing with the reaction-time task.

The group mean is shown on the righthand side of the figure, with a 95% interval based on between-subject differences.

Figure 4 shows psychometric functions from the middle pair of sessions for the three experienced

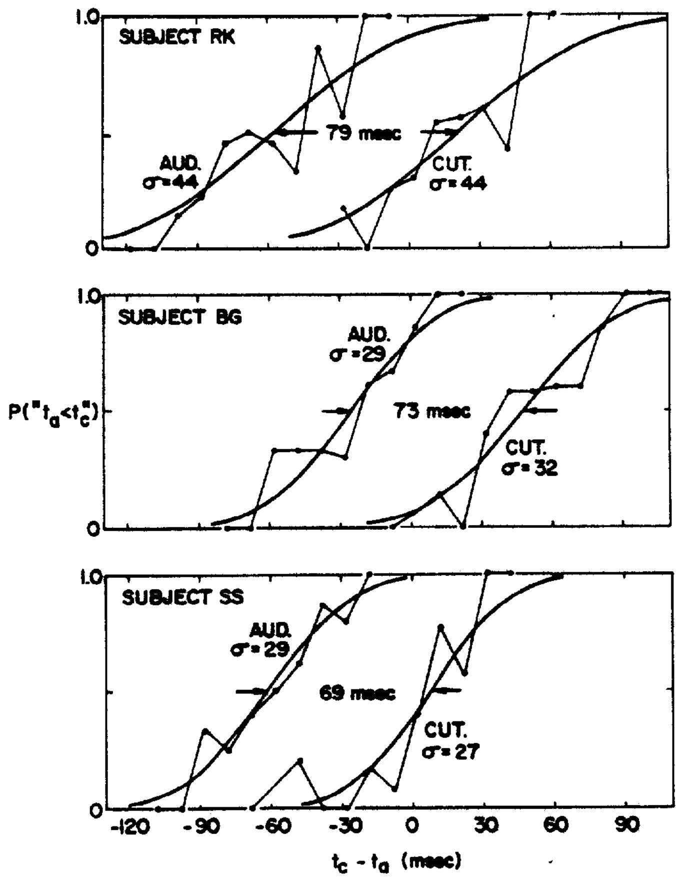

Figure 4

subjects.[15] All functions show the proportion of trials on which the auditory signal was reported as first. In each case, changing the attentional bias from auditory to cutaneous displaces the function to the right without changing its shape. Normal ogives were fitted by maximum likelihood, and the value of sigma measures the slope of the function. The form of the fitted function is not important; indeed, it could be argued that linear functions might fit better. The important point is that for these subjects the mean prior-entry effect, which is over 70 msec., is more than twice as large as the measure of slope. This means that the same stimulus pair can be consistently perceived in two different orders, depending on the state of attention.

Given a method of establishing a fairly stable prior-entry effect, we can now use it to ask questions about the way in which attentional bias operates in the processing of signals in two channels. The first approach we made to this problem was to study the relation between

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[15]Although our data were generated by a staircase procedure rather than the method of constant stimuli, we can still use them to estimate psychometric functions, regarding the staircase procedure as a method of locating observations in the region of interest. We have found from a series of Monte Carlo calculations that under the conditions of our experiments, the resulting bias is very small. A pleasant feature of this procedure is that observations are distributed around the 50% point of the psychometric function in such a way as to approximately equalize the sizes of the standard errors of the proportions. Data points at the centers of the functions in Fig. 4 are each based on about 11 observations; points at the extremes are based on about 3 observations. Each function is based on a total of about 75 observations.

signal intensity and the prior-entry effect. Figure 5 shows why this approach might be helpful.

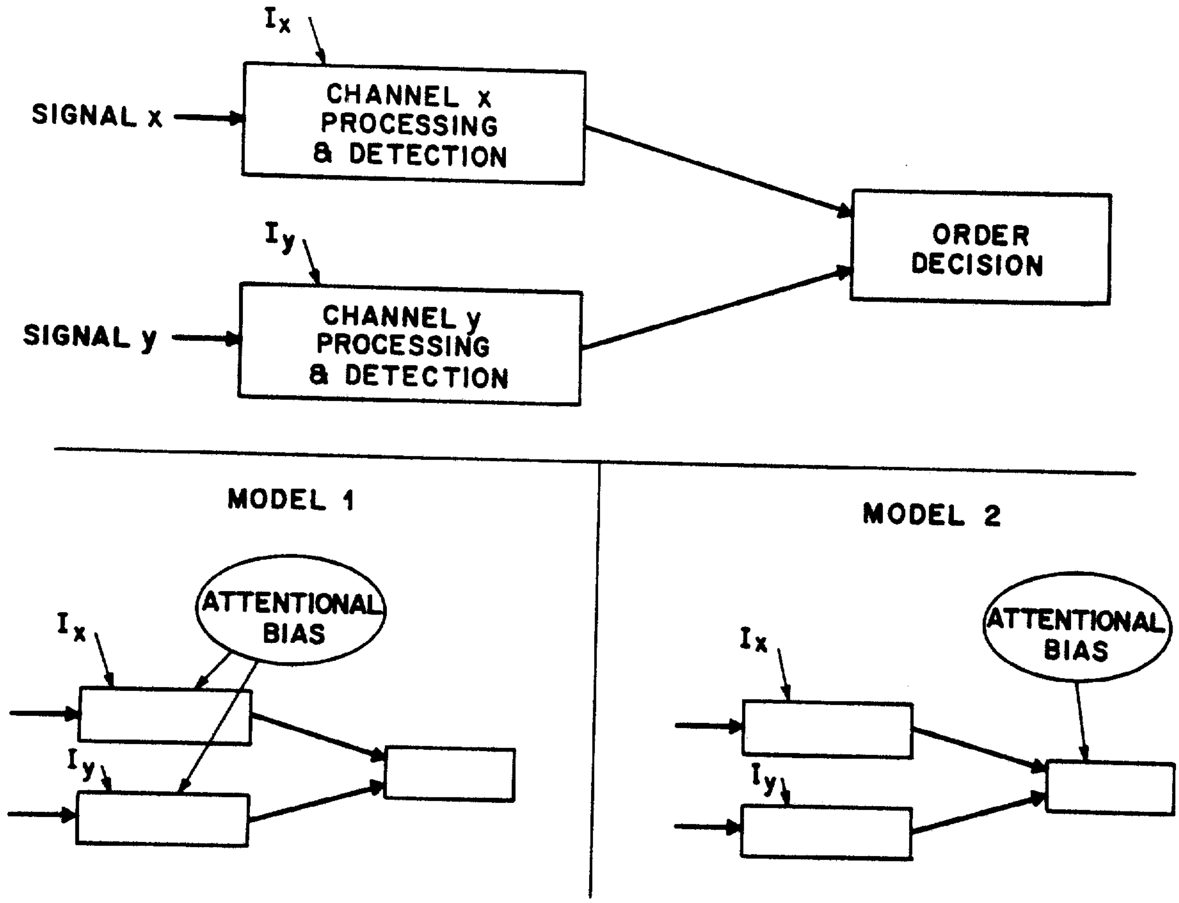

Figure 5

We assume that the initial processing of each signal is performed by separate and independent sensory channels. The detection of a signal occurs at a time that depends both on when the signal was presented, and on its detection latency. The order decision depends on the relative times of the two detections. As a working hypothesis, we assume that signal intensity influences only the early stage of processing: the higher the intensity I_x or I_y, the shorter the corresponding detection latency.

In a second experiment we tried to discriminate between the two models shown at the bottom of the slide. For each model, we expected the simultaneity point to be influenced both by intensity and by attentional bias. Consider Model 2 first. Here the bias has its effect, not because of changes in the sensory channel, but because it influences the more central order-decision. Given reasonable assumptions, the model can be shown to have the following property: The effects on the simultaneity point of intensity and bias must be additive.[16] In other words, given Model 2, the prior-entry effect should not depend on the intensity of the signals.

Now let us turn to Model 1. Here the attentional bias influences the channels themselves. The greater the bias toward a channel, the shorter its detection latency. In this model there is no reason to expect the effects of intensity and bias to be additive (Sternberg, 1969). Furthermore, all the interesting specific versions of this model that we know of lead to an interaction with intensity. Examples are changing the gain or attenuation of signals, varying the relative rates of rapid sampling in different channels, and adjusting a detection criterion (Lindsay, 1970; Moray, 1969; Treisman & Geffen, 1967; Zelnicker, 1971). Finally, all of these mechanisms lead us to expect that as we raise signal intensities, the prior-entry effect will become smaller. Figure 6 explains this for one particular mechanism (see Grice, 1968; John, 1967; Luce & Green, 1972).

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[16] See Appendix 2 for a statement of the model and a proof. This model is inconsistent with certain claims based on physiological data that attentional effects are mediated, at least in part, by mechanisms close to the periphery. But these claims have been disputed in recent years. (See Moray, 1969, Ch. 9, for a review, and Picton et al, 1971, for a recent study.)

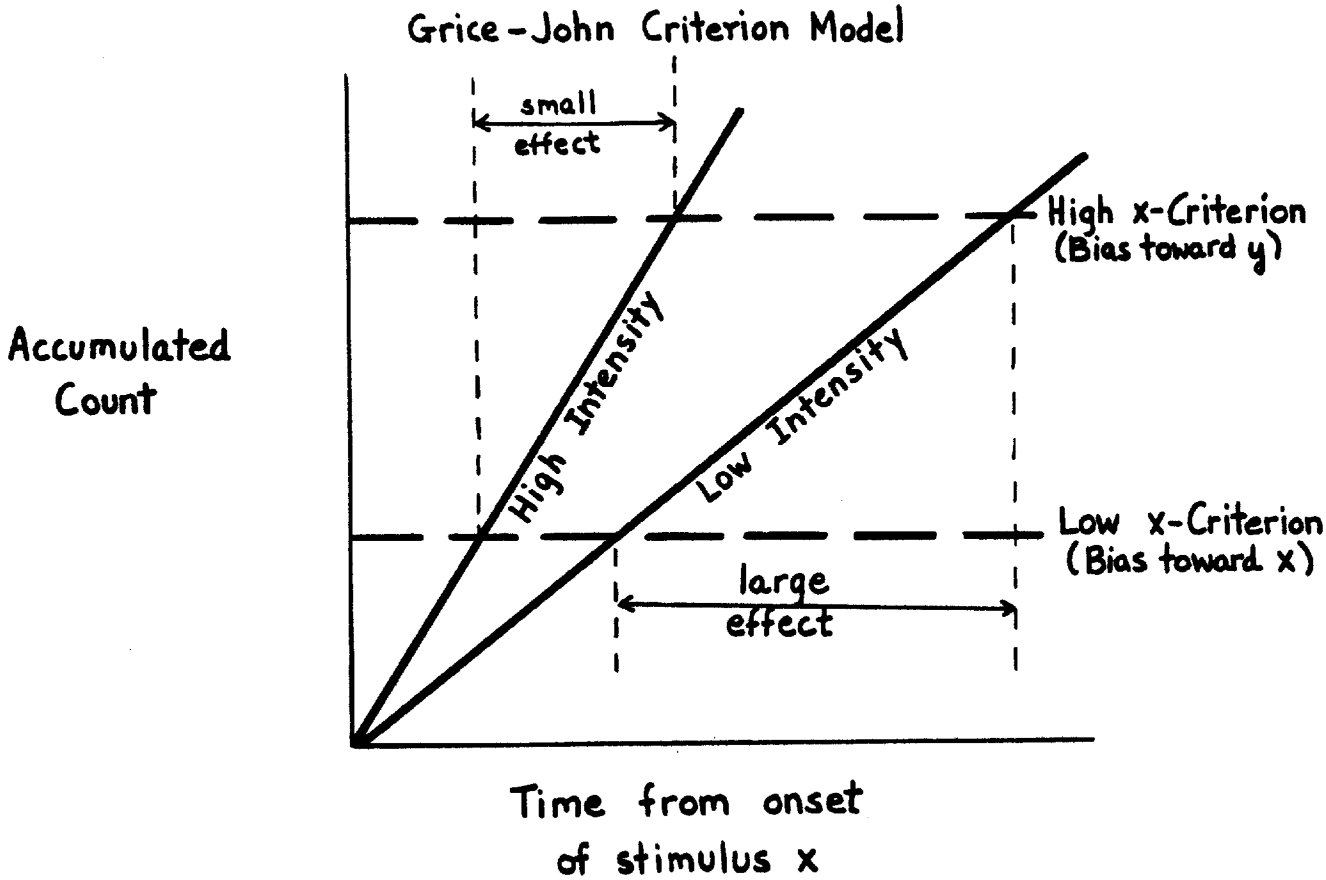

Figure 6

Suppose that an internal count produced by signal x accumulates over time at a rate that depends on its intensity. The figure shows the accumulated count as a function of time for high- and low-intensity signals. Detection occurs when the accumulation reaches a criterion. Now, suppose the criterion is changed from a low value, representing a bias toward that channel, to a high value, representing a bias toward the other channel. What effect would this criterion change have on the detection latency? The effect for the high-intensity signal would be smaller than the effect for the low-intensity signal. The result is that when both signals are of high intensity we expect a smaller prior-entry effect than when both are of low intensity.

To discriminate between attentional mechanisms in this class and those having the form of Model 2, we used our method to measure the prior-entry effect with three pairs of intensities. This time the signals were visual and auditory. The visual signal was the onset of a 1/2-degree spot of light, and the auditory signal was the onset of a burst of band-limited noise. Each signal was varied over three intensity levels in a correlated fashion, so that our conditions were low-low, medium-medium, and high-high. Visual intensities covered three log units, and auditory intensities covered 53 dB.

The experiment was addressed to two principal questions. First, would we observe a prior-entry effect with this pair of channels? And second, how would the effect depend on intensity?

The results are not as clearcut as we would like, because of large individual differences, and we hope to improve on them in the near future. Nonetheless, a few definite conclusions can be drawn. First, a prior-entry effect was revealed for this pair of channels also, although it is smaller than the effect in the auditory-cutaneous pair. It averaged about 30 msec. over the six subjects, rather than 55 msec. Second, the size of the effect was clearly not reduced by increasing the stimulus intensities, in the way that one would expect from most versions of Model 1. For the three experienced subjects, the average effect was about 45 msec. and was virtually constant with changes of intensity. These results support Model 2. But for the remaining subjects the effects actually increased with intensity, supporting a version of Model 1 that we find implausible. On the basis of the results so far, we favor Model 2, and hope to clarify the matter by improvements in method. For example, it may have been an error to vary the signal intensities from session to session, rather than doing it randomly from trial to trial.

In summary, the prior-entry effect appears to be real, even when refined methods are used and some potential artifacts removed. The perceived order of two events can be strongly influenced by attentional bias. This is true for auditory-cutaneous pairs and also for auditory-visual pairs. The effect takes the form of a horizontal displacement of the psychometric function. The existence of the effect in our experiments supports the assumption we started with - that requiring the observer to respond quickly and selectively to a signal biases his attention toward that signal. The possibility of a prior-entry effect limits interpretations that can be made of simultaneity experiments in which attentional bias has not been controlled.[17] Finally, we conclude tentatively that the locus of attentional biasing <u>follows</u> the detection of the signal, rather than preceeding it.

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[17] Since there is no reason to believe that the effect is limited to heteromodal stimulus pairs (see Needham, 1934, 1936), this possibility may be quite general. Indeed, Treisman's (1969) view that inputs to different analyzers (e.g., modalities) can be processed in parallel more readily than inputs to the same analyzer might lead one to expect <u>more</u> marked prior-entry effects for stimuli in the same modality. This expectation is also consistent with the finding of LaBerge et al (1970) that although the biasing effect of unbalanced stimulus probabilities generalizes to the discrimination time for other stimuli in the same modality, the amount of generalization is relatively small.

APPENDIX 1

We present in Fig. 7 our analysis of S. S. Stone's (1926) data. To make her data comparable to ours, we have plotted the proportions P("$t_a<t_c$) + P("$t_a=t_c$")/2; each point is based on 50 observations. Normal ogives were fitted by maximum likelihood (probit analysis). Fitting pairs of ogives to P("$t_a<t_c$") and P("$t_a<t_c$")+P("$t_a=t_c$") = 1-P("$t_a>t_c$") separately in each attentional condition produced similar patterns of results; parameters of the fitted ogives are given in Table 1.

TABLE 1

		P("$t_a<t_c$")		1-P("$t_a>t_c$")	
Subject	Parameter	AUD.	CUT.	AUD.	CUT.
B	$\hat{\mu}$	89	128	60	93
	$\hat{\sigma}$	28	43	21	27
P	$\hat{\mu}$	77	110	5	52
	$\hat{\sigma}$	50	40	35	47
M	$\hat{\mu}$	64	112	25	96
	$\hat{\sigma}$	79	70	77	86

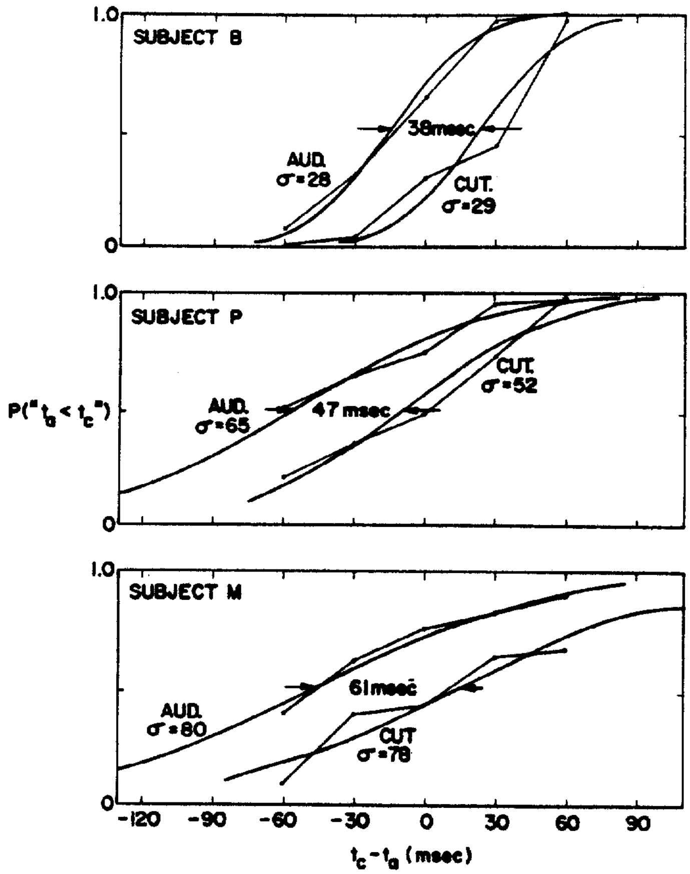
SUBJECT B
AUD.
σ=28
38msec
CUT.
σ=29
SUBJECT P
AUD.
σ=65
47 msec
CUT.
σ=52
SUBJECT M
AUD.
σ=80
61msec
CUT
σ=78
P("t_a < t_c")
1.0
0
-120 -90 -60 -30 0 30 60 90
t_c - t_a (msec)

Figure 7

APPENDIX 2

Here we present a statement of the independent-channels model and derive enough of its properties to show that Model 2 of Fig. 5 implies that the effects of attentional bias should be independent of stimulus intensity. For more extensive discussion of implications of the independent-channels model, and some tests, see Sternberg & Knoll, 1971.

Let stimulus s_x be presented at time $t_x=0$ and let stimulus s_y occur at time $t_y=d$. Let the random variables R_x and R_y be the two detection latencies. Assume that R_x and R_y are unaffected by the value of d, are independent in mean, and are stochastically independent. The detection times (or "central arrival" times) are $U_x=R_x$ and $U_y=R_y+d$.

We assume that the order decision depends on the difference, U_y-U_x, between these arrival times. That is, the probability of the response "s_x first" or "$t_x<t_y$" depends on U_y-U_x and can be represented by a function $F(U_y-U_x)$:

$$P(\text{"}t_x < t_y\text{"}) = F(U_y-U_x) \tag{1}$$

The simplest F is a step function:

$$F(U_y-U_x) = \begin{cases} 0, & U_y-U_x < \delta \\ 1, & U_y-U_x \geq \delta. \end{cases} \tag{2}$$

This represents a <u>deterministic decision function</u>. More generally, let F be any nondecreasing function whose range is the unit interval. This represents a <u>probabilistic decision function</u>. Let Δ be the random variable whose (cumulative) distribution function is F:

$$F_{\Delta}(U_y - U_x) \equiv P(\Delta \leq U_y - U_x) \tag{3}$$

Then

$$\begin{aligned} P(\text{"}t_x < t_y\text{"}) &= P(\Delta < U_y - U_x) \\ &= P(U_x - U_y + \Delta < 0) \\ &= P(R_x - R_y + \Delta < d). \end{aligned} \tag{4}$$

Now consider $P(\text{"}t_x < t_y\text{"})$ as a function of d - that is, as a psychometric function:

$$g(d) = P(\text{"}t_x < t_y\text{"} | d).$$

Then it is clear that

$$g(d) = P(R_x - R_y + \Delta < d), \tag{5}$$

so that the psychometric function estimates the distribution function of the sum of random variables: $R_x - R_y + \Delta$. That is, the psychometric function is the convolution of the distribution of arrival-time differences, $R_x - R_y$, and the decision function.

For the deterministic decision function, Eq. 2, the psychometric function is given by

$$g(d) = P(R_x - R_y + \delta < d),$$

or

$$g(d) = P(R_x - R_y < d - \delta). \tag{6}$$

Now, let the stimulus intensities be I_x and I_y, and let A denote the attentional bias. In Model 2, each of these factors is assumed to have selective effects on only one process:

$$\begin{aligned} R_x &= R_x(I_x) \\ R_y &= R_y(I_y) \\ \Delta &= \Delta(A). \end{aligned} \qquad (6)$$

The consequence is that these three factors have additive effects on the mean, variance, and all the higher cumulants of the sum $R_x(I_x) - R_y(I_y) + \Delta(A)$, and therefore on the cumulants of the psychometric function. This means that changing A induces changes in the mean and higher cumulants of the psychometric function that are independent of the values of I_x and I_y. (It also means, of course, that the effects of changes in I_x and I_y must be additive in the same sense.) Note that, <u>in general</u>, this <u>does not</u> imply additivity for effects on the median (50%-point) of the psychometric function.

For the deterministic decision function, whose psychometric function given by Eq. 6, attentional bias can influence only the value of the constant, δ. A change in δ corresponds to a horizontal displacement (translation) of the psychometric function, with no change in shape.

For the general decision function, if the effect of changing the attentional bias is to cause a translation of the function, F, the effect is again to produce merely a translation of the psychometric function.

In both of the above instances, the effect of attentional bias on the 50%-point of the psychometric function (its median), which corresponds to our present definition of the prior-entry effect, is the same as the effect on its mean. This is also true for an arbitrary F, so long as the psychometric functions are symmetric. But in the general case, additivity of effects on the mean of the psychometric function can be tested only approximately by examining the 50%-point, so that either caution or more sophisticated estimation of the mean is called for.

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