Abrupt Visual Onsets and Selective Attention: Evidence From Visual Search

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The effect of temporal discontinuity on visual search was assessed by presenting a display in which one item had an abrupt onset, while other items were introduced by gradually removing line segments that camouflaged them. We hypothesized that an abrupt onset in a visual display would capture visual attention, giving this item a processing advantage over items lacking an abrupt leading edge. This prediction was confirmed in Experiment 1. We designed a second experiment to ensure that this finding was due to attentional factors rather than to sensory or perceptual ones. Experiment 3 replicated Experiment 1 and demonstrated that the procedure used to avoid abrupt onset—camouflage removal—did not require a gradual waveform. Implications of these findings for theories of attention are discussed.

The human visual system is exquisitely sensitive to relative movement and to flicker. The generality of this observation is readily apparent to anyone viewing a complex scene with a moving object in it: Until the movement begins, the object can seem completely invisible; at movement onset, the object's location is immediately and compellingly manifest, almost without effort on the part of the observer. The salience of flashing lights on ambulances and radio towers is similarly obvious. We are concerned in this article with determining what role, if any, spatial selective attention plays in the detection of such stimuli. In particular, we will test a hypothesis in the context of visual search which holds that isolated abrupt stimulus onsets cause a rapid and involuntary deployment of attention to the locus of the temporal discontinuity.

Visual Search and Attention

Estes and Wessel (1966) and Atkinson, Holmgren, and Juola (1969) were among the first to show that the time required to detect

a prespecified alphanumeric character among distractors increases nearly linearly as the number of distractors increases. This display size effect is a very robust finding that holds under a variety of experimental conditions. The implication of the display size effect is clear: When there is uncertainty about the location of the target in a visual display, a search must be conducted over locations occupied by potential targets. Furthermore, the search is constrained in its speed; several items cannot be evaluated as quickly as one. Instead, an increase in the number of potential targets taxes the capacity of the search mechanism to detect the target.

This pattern of results may be contrasted with those obtained in a visual search task in which subjects are informed about the target's location in advance of its presentation. By now there are many demonstrations of subjects' ability to allocate attention to a particular location while they maintain fixation. Investigators have commonly demonstrated this by using a precue to specify a location or set of locations that will contain information relevant to the task at hand. This method was used by Sperling (1960) in his classic study of visual persistence and has since been used by others to study selective spatial attention more directly (e.g., Colgate, Hoffman, & Eriksen, 1973; Engel, 1971; Eriksen & Hoffman, 1972, 1973; Jonides, 1980, 1981; Posner, 1980; Posner, Nissen, & Ogden, 1978). In these experiments, subjects have typically been asked to determine whether a prespecified target is present in a multielement display. When no locational precue is provided (Atkinson et al., 1969), reaction times increase roughly linearly with the number of elements in the display. When a bar marker reliably indicating the location of an upcoming target is provided (Holmgren, 1974), both overall reaction time (RT) and the slope of the regression line relating display size and latency are smaller than without a cue. Similar results are seen in the accuracy of responses under impoverished viewing conditions (Bashinski & Bacharach, 1980; Van der Heijden & Eerland, 1973). Furthermore, Shaw (1978) has shown that observers can take stimulus probabilities into account as they optimally allocate fixed attentional resources to multiple spatial locations.

These findings have generally been interpreted as showing that subjects can direct their attention to spatial positions in preparation for a display and can thereby reduce processing time by not having to localize probable targets as they do in an uncued situation. Put another way, the cue allows subjects to allocate scarce resources to a particular spatial channel in advance, resulting in rapid processing of whatever signal subsequently occupies that channel. This conclusion is compelling given that subjects cannot take advantage of cues that specify two noncontiguous spatial positions (Engel, 1971; Hoffman & Nelson, 1981; Posner, Snyder, & Davidson, 1980; but see Shaw, 1978).

The locus of control of shifts of visual attention can be either central or peripheral (Jonides, 1981; Posner, 1980). That is, a shift of attention may occur either because an observer chooses to execute one or because the occurrence of a peripheral visual event may automatically capture attention. This distinction was made by Jonides (1981) in a series of experiments exploring the effects of central and peripheral visual cues. He showed that abrupt peripheral locational cues, as compared with foveal ones, produced both faster reaction times and a greater difference between the benefits of a valid cue and the costs of an invalid one. From this result and others, Jonides concluded that shifts of visual attention elicited by peripheral stimuli are imperative and automatic, whereas those produced by central cues are less efficient and somehow less obligatory.

The identification of a mechanism that automatically directs attention to salient visual events in the periphery is consistent with the finding that simple stimulus features can often be used as the basis for item selection. When items are processed this way, subjects' search behavior mimics their behavior when they are cued about the location of an impending target. For example, Treisman and Gelade (1980) demonstrated that targets differing from nontargets in a simple way (e.g., Xs among Os) are easily detected, regardless of the number of distractor elements. Only when the target is defined by a conjunction of features (e.g., a red X among red Os and green Xs) must focal attention be applied to items serially. Similarly, Egeth, Jonides, and

Wall (1972) and Jonides and Gleitman (1972) showed that the detection of digits among letters could take place in parallel across the entire visual field, regardless of the number of distractor letters. In fact, it is possible with practice to develop new target categories that allow rapid, automatic detection (Rabbitt, 1967; Shiffrin & Schneider, 1977).

Results of this sort can be accommodated by a theory in which certain stimulus features (e.g., color) could be used as a basis for passing stimuli into a limited capacity system for further processing (Duncan, 1980). Each stimulus can be interviewed for features relevant to the task at hand, and stimuli possessing the appropriate features are immediately admitted to the limited capacity system.

In the experiments reported above, we explored a stimulus property—abruptness of onset—that may be used as a basis for admission into the limited-capacity system. The choice of this property is not arbitrary. If we consider some of the commonplace examples in which visual search seems intuitively to be directed by distal stimulus features, the ubiquity of sudden stimulus onset becomes apparent. Cases in which flashing lights capture our attention illustrate this point nicely. Furthermore, there is emerging electrophysiological and psychophysical evidence that abruptness of onset is a stimulus property to which the visual system is particularly sensitive. Let us briefly review some of this evidence before we describe our experiments.

Abrupt Onset in Visual Processing

Several investigators have explored the effect of temporal waveform on the detection of visual stimuli. This has been motivated in part by the electrophysiological finding that cells in the visual system are differentially sensitive to abrupt and sustained visual events (e.g., Cleland, Levick, & Sanderson, 1973), and the finding in psychophysics of visual channels or mechanisms that are selectively sensitive to specific temporal and spatial frequencies (e.g., Kulikowski & Tolhurst, 1973).

Electrophysiology

In 1966, Enroth-Cugell and Robson identified two distinct classes of ganglion cells in the cat's retina: the firing frequency of one class (denoted Y or transient cells) was enhanced at the abrupt onset and offset of a stimulus and only then; another class of cells (called X or sustained cells) exhibited continuously enhanced firing throughout the duration of the stimulus.

Subsequently, several other investigators corroborated and expanded on this finding. The two types of cells, it emerged, differ in several respects. Transient cell receptive fields have larger surrounds (Cleland et al., 1973) and are more sensitive to rapid flicker or motion (Fukada & Saito, 1971) than sustained cells are. Furthermore, the response latency of transient cells is shorter and their axonal propagation velocity is higher than that of sustained cells (Cleland et al., 1973; Fukada, 1973). Finally, Fukada and Stone (1974) found that the concentration of sustained-cell receptive fields is highest in the fovea, whereas transient receptive fields are more evenly distributed about the retina.

Psychophysics

Other investigators have found correspondences to the electrophysiological findings described above using psychophysical procedures and human subjects. Kulikowski and Tolhurst (1973) distinguished two visual thresholds for temporally modulated sinusoidal gratings: the contrast at which flicker could be detected and the contrast at which spatial structure could be identified. Flicker-detection sensitivity declined dramatically at high spatial frequencies and low temporal modulation frequencies. However, at low spatial frequencies, sensitivity to spatial structure declined, whereas changes in temporal frequency had little effect. Kulikowski and Tolhurst concluded that there are (at least) two independent mechanisms in the visual system, one sensitive to rapid flicker and low spatial frequency and the other sensitive to visual detail and form and high spatial frequency.

Subsequently, Tolhurst (1975) investigated the onset and offset characteristics of sustained and transient channels. In this experiment, sensitivity to a sinusoidal grating was measured when it was flashed for 4 ms at various times before, during, and after the presentation of a subthreshold 800-ms grating of the

same spatial frequency and phase. Tolhurst discovered that when the gratings were of low spatial frequency (2 cycles/deg), test flash sensitivity increased briefly at the onset and decreased briefly at the offset of the long flash. However, at a higher spatial frequency (7.6 cycles/deg), the sensitivity to the test flash increased to a steady level for the duration of the long flash.

Another demonstration of the importance of abrupt onset is a study by Breitmeyer and Julesz (1975) in which contrast sensitivity to sinusoidal gratings was assessed under either abrupt or gradual onset and offset. The gradual onsets were 200-ms linear ramps, and all gratings had the same time-averaged energy. Breitmeyer and Julesz found that sensitivity was enhanced at spatial frequencies less than 5 cycles/deg when the onset was abrupt as compared to when it was gradual; there was little effect of offset waveform.

Wilson (1978) also obtained contrast sensitivity functions for gratings of various spatial frequencies under two types of temporal modulation. Mean intensity of the gratings followed either a Gaussian function with a time constant of 250 ms (S-modulation), or one 125-ms cycle of a square wave (T-modulation). In agreement with the findings of Breitmeyer and Julesz (1975), T-modulation increased sensitivity at low spatial frequencies and reduced sensitivity at high spatial frequencies as compared to S-modulation. These examples suggest that abrupt onset has a special status in the visual system.

Reaction Time and Detection

This conclusion is supported by other experiments that explored the effects of abrupt change on the processing of visual stimuli. Todd and Van Gelder (1979) measured response latencies to suprathreshold stimuli having abrupt onsets or not. Rather than using a gradual onset contrasted with an abrupt one, as in the Breitmeyer and Julesz (1975) or Wilson (1978) studies, Todd and Van Gelder employed what they called the *no-onset* presentation procedure as a control. With this technique, stimuli are present before trial onset, but are completely camouflaged by irrelevant stimulus elements. The irrelevant elements are then removed at trial onset,

revealing the unchanging display items. This condition was contrasted with a standard abrupt onset procedure. In one experiment, eight asterisks were arrayed horizontally before the subject. At trial onset, seven of them disappeared, and subjects were required to execute a saccadic eye movement to the remaining target. Eye movement latency in this no-onset condition was compared to that in the onset condition in which a single target appeared abruptly in what had been an empty display field. Subjects were uniformly faster in the onset condition; this difference increased as the complexity of the decision to be made about the stimulus increased from one of detection and localization to one of categorization.

Following Todd and Van Gelder (1979), Krumhansl (1982) reported a study using a procedure similar to the onset–no-onset paradigm. A linear array of characteristics was presented in a prestimulus field (e.g., $|+x+x\cdot+x+x|$; $\cdot$ = fixation point). At trial onset, all but one location was extinguished; the remaining character was either identical with the character in that position in the prestimulus field, (no form change: $|\quad+\cdot\quad|$) or was different (form change: $|\quad x\cdot\quad|$). Pattern masks then terminated the display. Krumhansl found superior localization and identification accuracy in the form change than in the no-form change condition. Although this finding is consistent with the hypothesis that a form change represents an abrupt onset (or apparent movement) at the target location and hence may activate transient mechanisms, thereby summoning attention, Krumhansl derived a quantitative information-processing model that does not invoke transient mechanisms or attention (although she points out that her data do not rule out such mechanisms). The model assumes the initiation of a brief phase of rapid encoding with stimulus onset, followed by a period of relatively less rapid processing. The rapid phase occurs during the prestimulus array in both conditions; however, the form change condition renews the rapid phase at trial onset, whereas the no-form change does not, resulting in an advantage for the form change condition. We will return to this enhanced encoding model in the General Discussion.

Conclusion

All of the experiments described previously have consistently demonstrated a processing advantage conferred by a temporally abrupt leading edge. This has at times been explicitly equated with the recruitment of visual attention. Breitmeyer and Ganz (1976) asserted that the transient system responds to abrupt changes in the periphery, such as movement or flicker, and thus composes "part of an 'early warning system' that orients an organism and directs its attention to locations in visual space that potentially contain novel pattern information" (p. 31). Similar suggestions have been made by Ikeda and Wright (1972, pp. 796–798) and by Broadbent (1982), who stated, "It seems plausible that a sudden stimulus onset acts to increase intake [of information] from that sensory region and to decrease it from elsewhere . . . ." (p. 284) Indeed, all of these writers were anticipated by Tichener (1908), who said,

sudden stimuli and sudden changes of stimulus exert a familiar influence upon attention [p. 192] . . . sudden stimuli impinge upon nervous elements that have hitherto been free from stimulation of their particular kind, i.e., upon nervous elements of a high degree of excitability; and it is probable that the excitations which they set up suffer less dispersion and diffusion, within the nervous system, than the excitations resulting from gradual application of stimulus. (pp. 204–205)

None of the studies reported above, however, directly assess the extent to which an abrupt onset may capture attention. It is not enough to compare a single abrupt onset with multiple onsets; we must establish that it is the presence of a single abrupt onset itself that captures attention in the presence of other (nonabrupt) irrelevant items. One way to conceptualize this capture is in terms of the monitoring of several visual channels. A channel in this context refers to a group of receptive fields in the same retinal area or to a group of noncontiguous receptive fields all sensitive to the same spatial frequency (Graham, 1981). If the observer is limited in the number of channels that can be monitored simultaneously, then an allocation model like that described by Shaw (1978) may reasonably account for the performance of the system. It is not difficult to imagine a model in which the activation of a so-called transient channel causes a rapid shift of resources to the task of monitoring events on the activated channel.

Two patterns emerge, then: (a) Abrupt onset of an object tends to confer an advantage in visual processing, and (b) theories of attention often assume that although processing resources are scarce, the assignment of attention by an efficient allocation schedule (e.g., on the basis of a preparatory cue or salient stimulus feature) can overcome these limitations, resulting in quite efficient performance. How are these patterns related?

We suggest a simple hypothesis. Abrupt onset is a property to which the visual system is particularly sensitive. According to the hypothesis, attention is rapidly and involuntarily applied to visual stimuli (or channels containing stimuli) possessing this property (i.e., abrupt onset) when no other such stimuli are present. The first experiment tests one aspect of this hypothesis, namely the rapidity with which attentional resources are brought to bear upon the relevant stimuli.

Experiment 1

We employed a standard visual search task in which the targets and nontargets were not distinguishable on the basis of simple physical features (e.g., color; cf. Treisman & Gelade, 1980) or categorical status (e.g., alphanumeric class; cf. Egeth et al., 1972). Furthermore, the stimuli served as targets and as distractors equally often, preventing practice with a consistent set of target items. Thus the mapping of stimuli to responses was varied (Schneider & Shiffrin, 1977).

Display size was two or four items. We chose only two display sizes because we were interested in the relative magnitudes of the display size effect under various conditions, and not in the linearity of the display size functions. This goal dictates collection of data only at the endpoints of the display size functions.

We used a version of Todd and Van Gelder's (1979, Experiment 5) no-onset procedure to present items lacking an abrupt onset. We did this because of a fundamental problem associated with using gradual onset as in some previous studies (e.g., Breitmeyer & Julesz, 1975; Wilson, 1978): Our dependent variable is response latency, and the temporal

asynchrony inherent in using gradual versus abrupt onset would make interpretation of latencies difficult at best. The no-onset procedure circumvents this problem and at the same time minimizes (indeed, eliminates) change in the nonabrupt items.

The variable of interest here is onset type. On every trial, exactly one item had an abrupt onset, and the remaining items were presented via the modified no-onset procedure (Todd & Van Gelder, 1979) in which camouflaging premasks were removed gradually. The use of gradual camouflage removal was intended to reduce the possibility of attentional capture by abrupt offsets. On some trials, the target was the abrupt onset item; on other trials, the target was revealed gradually; on still others, of course, the target was absent altogether.

If the aforementioned hypothesis is correct, then the abrupt onset item, whether or not it is the target, is identified first on every trial. If on a particular trial the abrupt onset item is the target, scanning halts and a positive response is emitted. Otherwise, scanning continues in a serial, self-terminating manner or in an equivalent parallel limited capacity search (cf. Atkinson et al., 1969; Townsend, 1972). Consequently, the hypothesis predicts little increase in latency with display size when the target is presented abruptly, but the usual increase of about 40 ms/comparison when the target is of the no-onset type or is absent.

Method

Subjects. Eighteen University of Michigan undergraduates were paid $7 for participation in two 50-min sessions.

Apparatus and stimuli. A Digital Equipment Corporation (DEC) PDP-11/60 computer controlled stimulus presentation and response collection. Stimuli were displayed on the face of a DEC VT-11 graphics display device (P4 phosphor), and responses were made on a Hewlett-Packard Model 2621A terminal keyboard. Subjects were seated in a dimly lit sound-attenuating booth with an illuminance at the display screen of 25 lx.

The stimuli consisted of the letters *E, H, P, S,* and *U,* constructed by illuminating the appropriate five segments of a seven-segment character (see Figure 1 for examples). Letters subtended a visual angle of 1° in width and 1.9° in height from a viewing distance of 45 cm. They were situated 5.7° from fixation and occupied various subsets of the vertices of an imaginary hexagon with sides of 5.7°. This spatial separation is well outside the range of lateral interference typically found in masking studies

(Bouma, 1978; Wolford & Chambers, 1983) as well as outside the estimated 1° focus of attention (Eriksen & Hoffman, 1972).

The luminance of a test patch with approximately the same number of points as a letter was 11.1 cd/m², and the luminance of the blank screen was 0.7 cd/m².

Procedure. Trial events, illustrated in Figure 1, were as follows. Each trial began with a 1,000-ms intertrial interval. The target item for the trial was shown for 1,000 ms in the topmost display location and then extinguished. A central dot then appeared, upon which subjects remained fixated throughout the trial. A 500-ms pause ensued, followed by the presentation of three figure-8 premasks arranged in an upward-pointing equilateral triangle. After 1,000 ms, irrelevant display segments began to fade in a series of four luminance decrements.[1] The offset lasted 80 ms. During offset, all remaining segments stayed at a constant intensity. When display size was four, all three premasks changed gradually to letters; when it was two, one changed to a letter and the other two faded to blanks.

At the *end* of camouflage offset, one letter was abruptly illuminated in what had been a blank display location. Subjects were told to scan the resulting display to determine whether the prespecified target was present. If it was indeed present, a prespecified key was pressed with the right index finger; if the target was absent, another key was pressed with the left index finger. Several types of errors were possible, including an incorrect response, a failure to respond within 2,000 ms, or the depression of an irrelevant key. When an error occurred, a single beep was emitted by the terminal as feedback. The display was then extinguished, and the next trial began 1,000 ms later.

Reaction time was measured from the onset of the abrupt stimulus, that is, from the end of camouflage removal. Thus, in principle, subjects had up to 80 ms of "free viewing" of the no-onset stimuli as they were revealed over time. This timing of events was required to ensure that any advantage observed for onset items could be attributed only to attentional factors and not to perceptual ones. For instance, if the onset item appeared at the beginning of the gradual offset, an abrupt onset advantage could be interpreted as reflecting contrast differences rather than attentional capture.

Subjects were instructed to respond as quickly as possible while keeping errors to a minimum. They also were advised to maintain fixation at center.

Design. The two main variables, trial type and display size, were completely crossed. The three trial types were

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[1] So as to minimize the possible attention-capturing effects of abrupt offset, the camouflage was removed gradually, within the limits of the available equipment. This was accomplished by reducing the luminance of the irrelevant segments in the figure-8 premasks in four discrete luminance decrements situated 27 ms apart. Thus the last step, which completely extinguished the camouflage, occurred 81 ms after the first one. This looked like a constant, gradual fading. The objection may be raised that this staircase comprises several abrupt changes that could summon attention. This possibility is evaluated in Experiment 3.
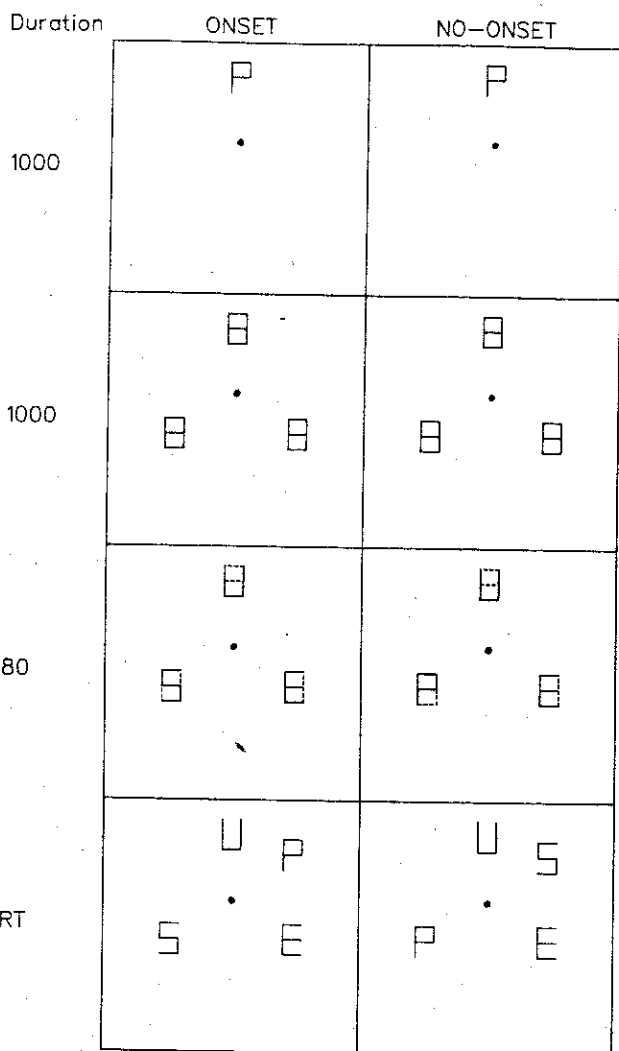
Figure 1. Sequence of events for a typical trial (display size = 4) in Experiment 1. (Dashes represent fading line segments. Duration in ms. The correct response for both trial types here is yes. Under display size = 2, not shown, two of the figure eights would fade to blanks.)

target present with an abrupt onset (or, for brevity, onset), target present with gradual camouflage removal (or no-onset) and target absent (or negative). Half the trials in each session required a positive response, and the remaining ones a negative response.

Display sizes of two and four occurred under each of the three trial type conditions. Exactly one onset item appeared in every test display, and the remaining items

Table 1
Number of Trials per Block in Each Condition of Experiment 1

Display size	Trial type		
	Onset	No-onset	Negative
2	10	10	20
4	5	15	20

Table 2
Mean Error Rates (%) For Each Condition and Display Size (2 and 4) in Experiment 1

	Onset		No-onset		Negative	
Day	2	4	2	4	2	4
1	3.6	4.9	7.9	7.3	3.4	3.4
2	3.2	3.1	5.4	6.2	3.2	3.0

were always no-onsets. When display size = 2, half the positive trials were onset and half no-onset. When display size = 4, however, only one quarter of the positive trials were onset, and the remaining were no-onset. These relative frequencies were chosen so that the occurrence of an abrupt onset was not itself correlated with the occurrence of a target; we thereby precluded the possible strategy of intentionally using the abrupt onset as a selection cue.[2] For clarity, the number of trials per block in each of the six conditions is shown in Table 1.

Each of the five letters served as target equally often in each condition and as the onset stimulus approximately equally often. The one onset item that appeared on each trial occupied each of the three onset display locations equally often. No letter was repeated in a display. Within these constraints, the trials were ordered randomly within 80-trial blocks.

Each subject completed four 80-trial blocks on each of two days, for a total of 640 observations per subject. Short rest periods were taken after every block.

Results and Discussion

The mean error rate across subjects and conditions was 4.4%. Error rates for each condition are shown in Table 2. In general, error rates were lower on Day 2 than on Day 1, were slightly higher when set size = 4 than when set size = 2, and were greater when the target was no-onset than when it was onset. These error rates are positively correlated with reaction time ($r = .23$); a speed–accuracy trade-off was not evident.

An analysis of variance was conducted on the mean reaction time data, the factors of which were days (1 and 2), trial type (onset,

[2] Note that (when display size = 4) this results in the target appearing in any one onset location only one twelfth of the time, but in any single no-onset location one fourth of the time. Were subjects aware of this contingency, they would be expected to optimally allocate attention toward the high-frequency (no-onset) locations and away from the low-frequency (onset) locations (Shaw, 1978), thereby reducing the probability of producing the predicted result.
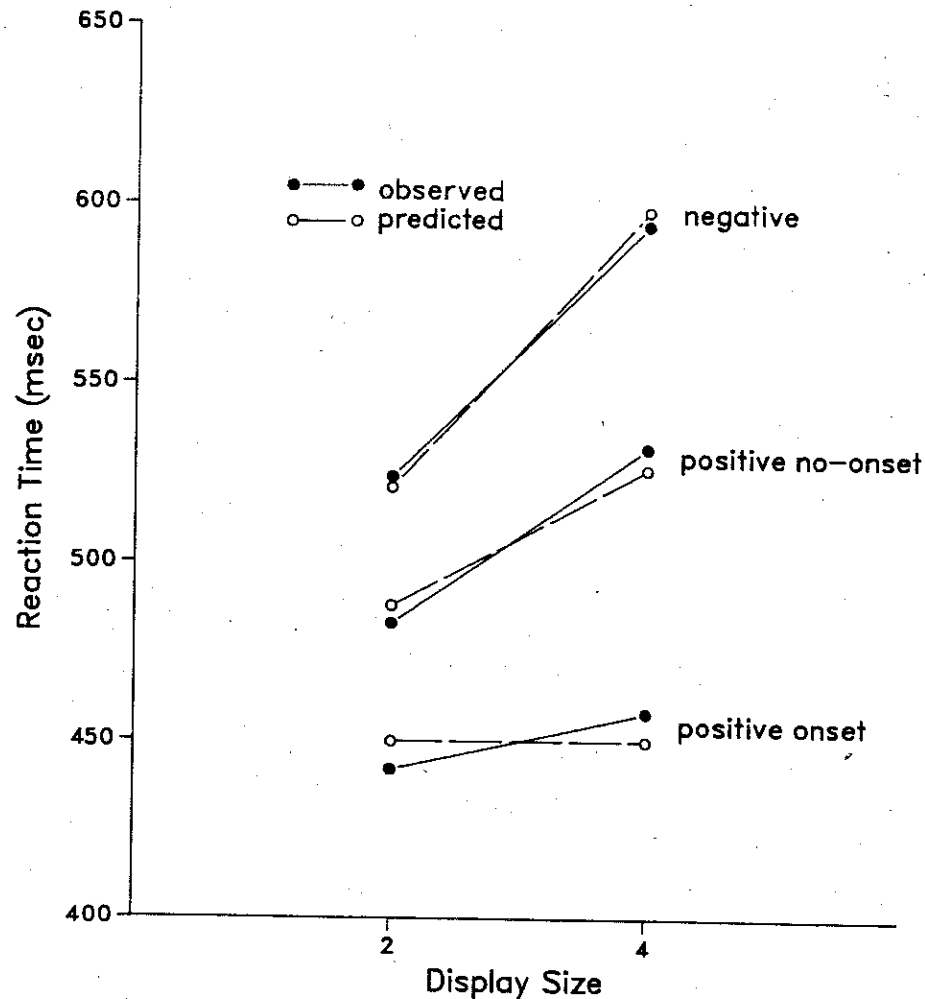
Figure 2. Mean reaction time on Day 2 as a function of display size. (Curve parameter is trial type. The number of trials per point is proportional to the entries in Table 1. See text for explanation of predicted points.)

no-onset, and negative), and display size (two and four). Large main effects of all the factors were found: For days, $F(1, 17) = 179$, $MS_e = 4,442$; for trial type, $F(2, 34) = 109$, $MS_e = 1,840$; and for display size, $F(1, 17) = 169$, $MS_e = 726$; all ps $< .001$. No interaction involving day was significant (all Fs < 1). Finally, the interaction between trial type and display size was highly significant, $F(2, 34) = 22.6$, $MS_e = 508$, $p < .001$.[3]

Given the lack of interaction involving day, we shall focus on data from the second session only, because they reflect more highly practiced performance and are therefore less variable. Mean Day 2 reaction times across all subjects are shown as the observed data points in Figure 2. An inspection of the figure shows that the increase in mean RT with increasing display size was not large when the target had an abrupt onset: The increment

in RT (or slope) was 7.9 ms/item. The onset slope contains zero in its 95% confidence interval, which was 9.04. The slope was larger when the target was no-onset (slope = 24.5 ms/item) and larger still when the target was absent (slope = 35.0 ms/item).[4] The Trial Type × Display Size interaction is readily apparent here.

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[3] Four of the subjects had exceedingly large error rates (greater than 10% in at least one condition). Because these subjects may have exhibited a speed–accuracy trade-off, the ANOVA was rerun excluding them. The pattern of results was unchanged: All the main effects were highly significant, and the only significant interaction was Trial Type X Set Size, $F(2, 26) = 22.15$, $MS_e = 469$, $p < .001$.

[4] Excluding the four error-prone subjects (see Footnote 3) gave slopes of 5.6, 23.3, and 36.4 ms/item for the onset, no-onset, and negative conditions, respectively.

Bonferroni multiple contrasts were conducted on the Day 2 data to determine the sources of the significant interaction. The differences between the slopes of each pair of trial types were all significant at the .05 level (the difference between the onset slope and the no-onset slope was 16.6; between the onset and negative slopes was 27.1; and between the no-onset and negative slopes was 10.5; a 95% simultaneous confidence interval is 9.04).

Quantitative model. We fit to the data a simple visual search model postulating that the abrupt onset item is scanned first on every trial but that otherwise the search is serial and self-terminating. We shall refer to this as the abrupt-capture model. This model bears some resemblance to Schneider and Shiffrin's (1977, p. 29) Model 1a. The model is expressed as

$$RT = A + kT + \delta N, \qquad (1)$$

where $E(A) = \alpha$, $E(T) = \tau$, $E(N) = \nu$, RT is a random variable representing reaction time, A is a random variable reflecting the time for all mental operations (e.g., encoding, motor programming, response execution) not accounted for by the other terms in the equation, k is the number of comparisons required on a trial, T is a random variable reflecting the time required to complete one comparison, δ is an indicator variable that equals 1 if the target is absent and 0 otherwise, N is a random variable corresponding to the extra time required to deal with a negative trial (Nickerson, 1965), and E denotes expected value. Under the model, k is exactly one when the target has an abrupt onset, no matter how many other items are present in the display. When the target is absent, k is equal to the display size d since the search is exhaustive in this case. When the target is present but has a gradual onset,

$$k = 1 + \frac{(d-1)+1}{2} = 1 + \frac{d}{2}.$$

The initial 1 in this equation corresponds to scanning the abrupt onset item, which by stipulation is not the target. This leaves $d - 1$ items to be scanned in a self-terminating search. The mean number of subsequent comparisons then will be $\frac{(d-1)+1}{2}$. (This

holds because the target appears in each location equally often in a random order.) Thus in the present case, $k = 2$ when the display size is two, and k has an expected value of 3 when the display size is four.

The values of k and δ under each of the conditions, as well as the observed response latencies, are displayed in Table 3.

Multiple regression of the data under this model gave estimates of the parameters as follows: $\hat{\alpha} = 411.9$, $\hat{\tau} = 38.1$, and $\hat{\nu} = 33.2$. The fit was quite satisfactory, accounting for 98.7% of the variance in the means with only three parameters.[5] The predicted means are shown in Table 3 and Figure 2. The estimate of 38.1 ms/comparison for the search parameter τ is in good agreement with other estimates in the literature (e.g., Schneider & Shiffrin's (1977) estimate of 42 ms/comparison and Sternberg's (1966) of 38 ms/comparison).

Root mean squared (*RMS*) error[6] was 5.9 ms, or less than 2% of mean RT. To further

Table 3

Parameters and Predictions of the Model, Day 2 Data Only, Experiment 1

Trial type	Display size	k	δ	Mean RT (ms)	
				Obs	Pred
Onset	2	1	0	441.8	450.0
Onset	4	1	0	457.7	450.0
No-onset	2	2	0	482.9	488.1
No-onset	4	3	0	531.9	526.2
Negative	2	2	1	524.4	521.3
Negative	4	4	1	594.4	597.6

Note. In the no-onset-4 condition, k is 3 on the average. All other values of k are exact. $R^2 = .987$. RT = reaction time; Obs = observed; Pred = predicted.

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[5] The abrupt capture model also makes predictions about variances under each condition (cf. Schneider & Shiffrin, 1977, Appendix G). The fit of the predicted variances to our data was not good. In particular, under conditions for which a disproportionately large amount of variance was predicted (i.e., those in which different numbers of comparisons are made across trials), we observed even more variance than predicted. The standard error of the observed variances was quite large, however, and so our ability to reject any plausible model was weak.

[6] *RMS* error is defined as

$$\left[\frac{1}{n} \sum_{i=1}^{n} (\text{obs}_i - \text{pred}_i)^2 \right]^{1/2}.$$

assess the adequacy of the model, fits were performed using the means from each condition for each subject individually. The median proportion of variance accounted for by the model within each subject was .933 (range: .58–.99). The parameter estimates were similarly reasonable for individuals; for instance, the median τ obtained was 38 ms/comparison (range: 15–61).[7]

We fit several other plausible models, including Model 1, a parallel, limited capacity, abrupt-capture model that mimics the serial, capture model (Atkinson et al., 1969; Townsend, 1972); Model 2, a parallel, unlimited capacity, capture model that does not allow for display size effects; Model 3, a parallel-capture model that requires a serial re-search of the display set on negative trials; and Model 4, a standard serial model with no provision for abrupt capture. (See the Appendix for further description of these models.) None of these models fit the data as well as the serial-capture model did, although Model 1 did almost as well. The proportions of variance accounted for by Models 1 through 4 were .985, .761, .895, and .772, respectively, as compared to .987 for the serial abrupt capture model. RMS error values for Models 1–4 were 6.3, 25.1, 18.8, and 24.5 ms, respectively, whereas the value for the serial abrupt-capture model was 5.9 ms. The contrasts in these fits underline the quality of the serial abrupt-capture fit. We prefer the serial abrupt-capture model to the parallel, limited capacity model because the latter predicts parallel slopes for the negative and no-onset conditions, whereas our analysis revealed a significant deviation from this pattern ($p <$ .05; see previous discussion of results).

From these results we conclude that the data are well described as being generated by a process that scans the single onset location first and all other locations serially in a random order until a target is found or the search is complete.

Experiment 2

The critical independent variable in Experiment 1 was onset type, and the conclusions to be drawn from the results of that experiment depend on the assumption that gradual no-onsets as instantiated in this study

are not perceptually more difficult to process than abrupt onsets are. But this assumption may be false. For instance, the visual receptors may adapt to the figure-8 premasks, resulting in reduced sensitivity at locations they occupy. Because we are claiming that the effect of abrupt onset is to summon attention when it is not already directed to the abrupt onset stimulus location, then the processing advantage an abrupt item confers should decline or disappear if attention is appropriately directed in advance. Indeed, in such a case the subject may be able to make better use of the preview afforded by the gradual target revelation and thereby show an advantage for no-onset stimuli. However, if the advantage of abrupt onset in Experiment 1 was not due to attentional factors, then the advantage should remain when attention is appropriately directed in advance.

Experiment 2 was conducted to test these predictions and thus to distinguish between a perceptual and an attentional explanation for the effects observed in Experiment 1. Subjects were required on each trial to identify a single letter that occupied a known location; in some blocks, the item had an abrupt onset, and in others, it appeared via the modified no-onset procedure used in Experiment 1. Eye position was monitored to ensure that departures from fixation were detected and admonished. Thus the retinal eccentricities of Experiment 1 were maintained.

Method

Subjects. Twenty undergraduates with uncorrected normal vision (11 female, 9 male) each served in a single 30-min session. None had served in Experiment 1. Compensation was $3.

Apparatus and stimuli. In addition to the equipment used in Experiment 1, a Gulf and Western model 200 scleral reflectance eye movement monitor was used to

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[7] One aspect of the capture model that remains unspecified is whether search is consistently ordered, and if so, how it is ordered. To investigate this issue, we calculated mean response times to no-onset targets when the display size = 4 (all other cases are degenerate) as a function of onset item location. No consistent ordering of response times was observed, including (a) clockwise or counterclockwise from the onset location and (b) locations near the onset item first and opposite the onset item last. Insofar as our data can reveal, then, search in this task is not consistently ordered.

determine eye position. Eye movement data were collected through an analog-to-digital (A/D) converter on the PDP-11/60 computer.

Head position was maintained by a chinrest. Subject's eye position was calibrated at the beginning of each 30-trial block and again whenever departures from fixation were detected on 3 trials since the last calibration run. A simple position criterion ($\pm 2°$ from fixation) was used to detect eye movements toward any of the display locations. Because the monitor was configured to measure only horizontal movements, glances directly upward or downward could not be detected. Subjects were unaware of this. Nevertheless, in the analyses below, trials are partitioned into those with vertical and those with non-vertical display locations in order to reveal possible differences due to undetected vertical movements.

Eye movement calibration. All eye position sampling via the A/D converter was at 1 kHz. Calibration consisted of sampling for 50 ms at each of five eye positions, corresponding to fixation, $\pm 2°$, and $\pm 4°$, run in random order. Conversion from A/D units to gaze position was through linear interpolation. Preliminary tests showed that observers could not voluntarily move their eyes or heads without such movement being detected.

Procedure. The sequence of events on each trial (see Figure 3) was as follows. A single target letter appeared at fixation for 1,000 ms. The target was replaced by a fixation cross, which remained throughout the duration of the trial. After 150 ms, an indicator rectangle appeared at one of the six possible display locations. During no-onset blocks, the indicator was a block figure 8; during onset blocks, the indicator was a configuration of six dots at the vertices of a block figure 8. The indicator was present for 1,000 ms. The procedure for the two types of blocks differs somewhat at this point. For no-onset blocks, irrelevant segments began to fade as in Experiment 1 over a period of 80 ms, gradually revealing the display item (see Footnote 1). For onset blocks, the six-dot configuration began to fade as a whole over an 80-ms period. At the instant the dots were gone, the display item was abruptly illuminated at that location. The display item remained until a response was made, at which time feedback appeared for 500 ms. A 1,000-ms intertrial interval followed.

Subjects were told that the purpose of the indicator was to allow them to prepare in advance for the display item: They were asked to "pay attention" to the spatial location occupied by the indicator, because the display item would appear there after a consistent delay. They were further informed that they should do this while maintaining fixation. The working principles of the monitor were briefly described.

Subjcts were instructed to respond as quickly as possible while making very few errors. A positive response was required if the display item was identical to the target; otherwise a negative response was called for. As in Experiment 1, response latencies were measured from the end of the camouflage removal, or, equivalently, from the onset of the abrupt-onset item. A beep after each error served as feedback. If an eye movement was detected, the beep sounded, and the trial response was discarded. All trials during which departures from fixation were detected were rerun at the end of each block. As mentioned earlier, if movements were detected on three trials

within a block, the calibration routine was automatically invoked.

Design. All five letters served equally often as the target. One half of the trials required positive responses, the rest negative. On negative trials, the display item was chosen randomly from the four nontarget items for that trial. Each target also appeared at each display position equally often. Two blocks of 30 trials each (plus rerun trials) were completed with abrupt onsets, and two with no-onsets. Onset type (no-onset, N, or onset, O) and response (positive or negative) were completely crossed within-subject variables. Order of blocks (onset or no-onset first) was a between-subject variable. Half the subjects ran with blocks ordered ONON, and the rest with NONO.

Results and Discussion

Eye movements were detected on 8.7% of the trials. Many of these can probably be attributed to inadvertent head movements
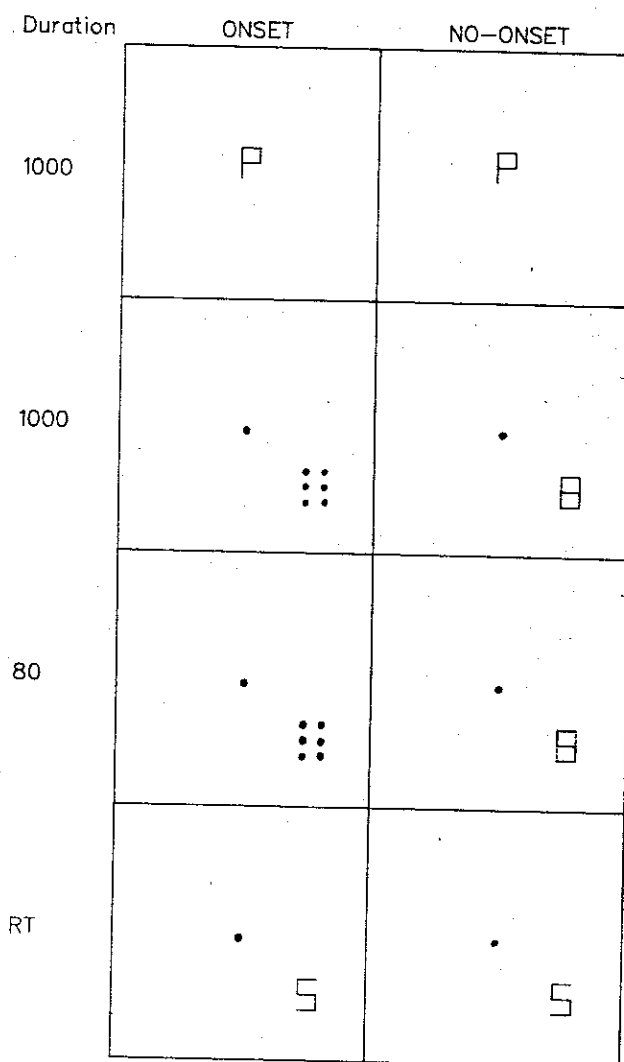

Figure 3. Sequence of events for a typical trial in Experiment 2. (Dashes represent fading line segments. The correct response for both trial types here is no.)

permitted by the unintrusive chinrest used. Nevertheless, we discarded all trials during which movements were detected; these trials are not included in what follows.

The mean error rate across all conditions was 7.2%. The somewhat higher error rate observed here is probably due to the relatively small amount of practice in this experiment. Overall, subjects were less accurate in the condition with which they began. Errors were positively correlated with RT ($r = .75$), indicating the absence of speed–accuracy trade-off.

Mean RT for each group and condition is shown in Table 4. The practice effect evidenced in the error data is clearly apparent here: Subjects were slowest in the condition in which they started. Overall, however, subjects were 10.6 ms faster when the display item appeared in the gradual, no-onset fashion of Todd and Van Gelder (1979) than via the standard abrupt-onset method.

To assess the magnitude of these effects, an analysis of variance was conducted with order as a between-subjects variable (onset or no-onset block first) and onset type (onset or no-onset) and response (positive or negative) as within-subjects variables. Subjects were faster on positive than on negative trials, $F(1, 18) = 42.4$, $MS_e = 1,258$, $p < .001$. The main effect of onset type, however, did not attain significance, $F(1, 18) = 1.4$, $MS_e = 1,624$, $p > .20$, although no-onset RT was 10.6 ms faster than onset RT ($SE = 10.1$ ms). The practice effect is seen in the significant Order × Trial Type interaction, $F(1, 18) = 5.6$, $MS_e = 1,623$, $p < .05$: Subjects improved more when they began with an onset block than when they began with a no-onset block. This interaction suggests that with practice, subjects were better able to take advantage of the 80 ms of preview afforded by the gradual camouflage removal.

The analysis was repeated excluding vertical trials, that is, trials on which the target appeared directly above or below fixation. These are trials on which any eye movements would have escaped detection. The pattern of results was the same: Positive responses were faster than negative ones, $F(1, 18) = 16.5$, $MS_e = 2,268$, $p < .001$, but again, although no-onset RTs were faster than onset RTs by 2.2 ms, this difference did not attain significance

Table 4

Mean Reaction Time and Standard Error (ms) in Each Condition of Experiment 2

Order of conditions	Abrupt onset		Gradual onset	
	M	SE	M	SE
Onset–No-onset	526	21	492	23
No-onset–Onset	534	25	546	24
Combined	530	16	519	17

($F < 1$). Apparently, then, eye movements cannot account for these results.

To further evaluate the onset–no-onset difference, we attempted to remove the practice effect seen as an interaction in Table 4. Mean reaction times for the four blocks, collapsed across conditions, were 596, 520, 508, and 513 ms, respectively, suggesting asymptotic performance by Block 3. An analysis of variance as above was therefore conducted on Blocks 3 and 4 only to determine whether, after practice, gradual presentation produces responses as fast or faster than abrupt onsets when attention is appropriately allocated. Mean no-onset RT was 13 ms faster than mean onset RT, but once again this difference was not significant, $F(1, 18) = 2.0$, $MS_e = 1,676$, $p > .10$. Of the remaining effects and interactions, only the response type F ratio exceeded unity, $F(1, 18) = 26.2$, $MS_e = 1,999$, $p < .001$.

In summary, the results of Experiment 2 indicate that when attention is appropriately directed in advance of a visual display, there is no advantage for abrupt onsets over gradual no-onsets. The pattern of results obtained in Experiment 1 cannot be attributed to perceptual or sensory factors. Instead, an explanation of that experiment based on attentional capture is supported.

These results may seem somewhat inconsistent with some findings reported by Todd and Van Gelder (1979). In particular, Experiments 3 and 4 in that article involved the use of precues that provided some locational information about upcoming stimulus events. In principle, following the reasoning used here, subjects in those experiments ought to have been able to allocate their attention to the cued locations in advance and thereby

eliminate the latency difference between onset and no-onset. In contrast, Todd and Van Gelder found a large effect of onset type on cued trials. Two aspects of their procedure, however, may have precluded the effective assignment of attention before trial onset. First, the cues were only partially valid: On 25% of the trials, the stimulus appeared in an uncued location. Second, the cues indicated two spatial locations that were at least 5° and as much as 20° of visual angle apart. Hoffman and Nelson (1981), Posner et al. (1980), and others have shown that subjects cannot simultaneously attend to multiple noncontiguous spatial locations efficiently. Thus Todd and Van Gelder's cuing procedure should not be viewed as an effective attentional manipulation.

The fact that no-onset RT was only 10.6 ms faster than onset RT deserves some comment. One might expect that because no-onset stimuli began to be revealed 80 ms before the clock started, they might result in responses that were as much as 80 ms faster than those to onset stimuli. There are two reasons to doubt this. First, the no-onset items did not become clearly discriminable until perhaps 20–40 ms before the clock started. Thus the 80 ms figure is an overestimate of the "preview time." Second, there is some reason to suspect that RTs to onset stimuli may indeed be faster than to no-onset stimuli after attentional effects have been minimized (Todd & Van Gelder, 1979, Experiment 3). Thus the latency advantage for no-onset stimuli is smaller than the preview duration might suggest. The important point from this experiment is that the advantage for onset stimuli vanishes when attention is appropriately directed in advance of an abrupt event, demonstrating the attentional nature of the advantage.

Experiment 3

In Experiment 1, we altered Todd and Van Gelder's (1979) no-onset procedure by removing the camouflage gradually rather than abruptly. Our reason for doing this was to minimize the possible attention-capturing effects of abrupt offsets. There is evidence from both electrophysiology (Ikeda & Wright, 1974) and psychophysics (Kulikowski & Tolhurst,

1975) that the transient system responds to offsets as well as to onsets. Consequently, to optimize our test, we avoided abrupt offsets.

However, there is reason to believe that this precaution was not necessary. For instance, Breitmeyer and Julesz (1975) found enhanced contrast sensitivity to gratings with abrupt leading edges and gradual trailing edges, but not to ones with only abrupt trailing edges, suggesting the visual system is not as sensitive to offsets as to onsets. Furthermore, Todd and Van Gelder (1979) used only abrupt offsets in their no-onset experiments and still obtained large effects. In fact, they found that increasing the number of irrelevant abrupt offsets facilitated RTs to no-onset items. Offsets, then, may have a fundamentally different attentional status than onsets do.

In Experiment 3, we replicated Experiment 1 twice within subjects: Camouflage was removed either with an 80-ms Gaussian offset function or abruptly. These two offset types were randomly intermixed. The apparatus used in Experiment 3 was an improvement over that used in Experiment 1: Here we used seven-segment light-emitting diodes (LEDs) driven by a digital-to-analog converter allowing nearly continuous intensity changes and thus smooth temporal waveforms. We could therefore assess the adequacy of the offset step function employed in Experiment 1 (see Footnote 1).

Method

Subjects. Nineteen University of Michigan undergraduates participated in two 50-min sessions. None of these people had served in Experiments 1 or 2, and each was paid $7 for his or her time.

Apparatus and stimuli. In order to effect greater control over the temporal waveform of the onsets and offsets of the stimuli, we constructed a display device consisting of six 7-segment LEDs (Jimpak #DL-750) and an array of digital logic to control the individual LED segments. The hardware logic was under software control via a digital output interface. The LED segments were driven by the digital-to-analog (D/A) converter of a DEC PDP-11/34 computer. The D/A converter was configured to output voltages at 1 kHz, so that voltages could be altered once per millisecond. There were 1,024 functional voltage levels. Letters with abrupt onsets were illuminated through the action of a single digitally controlled relay.

In removing the camouflaging LED segments, we employed a Gaussian offset function similar to that employed by Wilson (1978); its duration was 80 ms from
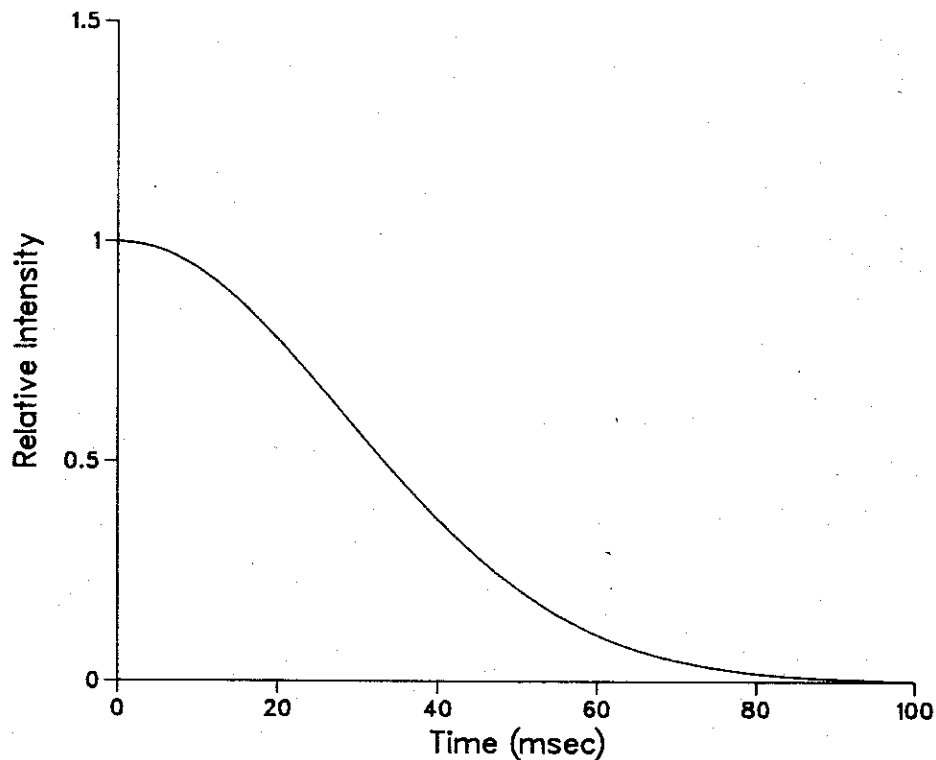
Figure 4. Temporal luminance profile of camouflage removal in Experiment 3.

completely on to entirely off. The equation for the Gaussian (with t in ms) was

$$I(t) = \exp[-(t/40)^2],$$

where I is relative intensity and $0 \leq t \leq 80$.[8] Figure 4 shows the temporal luminance profile. At their maximum brightness, each letter had a luminance of 5.6 cd/m^2. The luminance of the blank display screen was 1.8 cd/m^2, and general booth illuminance was 190 lx at the display surface.

The LEDs were arrayed at the vertices of an imaginary hexagon centered about fixation. The LEDs were 5.7° from fixation and 5.7° apart center to center. Each of the five-segment letters (E, H, P, S, and U) subtended 1.9° of visual angle in height and .95° in width. The LEDs were mounted in a flat black display surface 60 cm (53°) high and 50 cm (48°) wide. All visual angles were measured from a viewing distance of 45 cm.

The LED display was controlled and responses collected by a DEC PDP 11/34 computer. Subjects responded by pressing the appropriate keys on a Hewlett-Packard 2621A terminal keyboard. Subjects were seated in a sound-attenuating booth illuminated by a fluorescent bulb located above and behind them.

Procedure. The procedure was identical to that used in Experiment 1, with the exception that on half the trials the irrelevant segments were removed abruptly, whereas on the remaining trials the irrelevant segments were removed via an 80-ms half-Gaussian (see Figure 4). The design of Experiment 1 was thus replicated twice, once with abrupt camouflage removal and once with gradual camouflage removal, with the two trial types randomly intermixed. Subjects were not informed of this fact, and upon debriefing none reported having any awareness of it. Subjects completed 6 blocks of 80 trials on each of 2 days, for a total of 960 trials per subject.

Results and Discussion

The mean overall error rate collapsed across days, subjects, and conditions was 5.4%. Error rates for each condition are shown in Table 5. As before, error rates for the various conditions correlated positively with the associated reaction times ($r = .41$), indicating the absence of a speed–accuracy trade-off.

An ANOVA was performed on the mean RTs with the following factors: day (1 or 2), camouflage removal waveform (abrupt or gradual), trial type (onset, no-onset, or negative), and display size (two or four). All of the main effects were highly significant: $F(1, 18) = 59$ for day, $F(1, 18) = 106$ for camouflage waveform, $F(2, 36) = 133$ for trial

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[8] The intensity of LEDs is known to vary linearly with current but not with voltage (cf. Nygaard & Frumkes, 1982). Because we intended to vary the intensity of individual LED segments via voltage changes in the D/A converter, we empirically determined the function relating voltage to intensity (or current). The relation between voltage and current was quadratic. We compensated for this nonlinearity in our voltage output function.

Table 5

Mean Error Rates (%) for Each Condition and Display Size (2 and 4) in Experiment 3

Camouflage removal	Onset		No-onset		Negative	
	2	4	2	4	2	4
Day 1						
Gradual	5.7	5.2	8.2	8.7	8.9	7.0
Abrupt	4.5	6.6	7.9	12.1	6.2	8.2
Day 2						
Gradual	3.1	1.7	3.6	5.2	3.0	2.1
Abrupt	2.7	3.0	4.4	5.2	3.4	3.0

type, and $F(1, 18) = 146$ for display size, all $ps < .001$. No interaction involving day was significant (all $ps > .05$). As in Experiment 1, the interaction between trial type and display size was significant, $F(2, 36) = 23.2$, $MS_e = 753$, $p < .001$; again, the display size effect depended upon the trial type.

We shall once again concentrate on the more highly practiced Day 2 performance in what follows, given the lack of interaction involving day. Mean response times are shown as the observed points in Figure 5. Of particular importance in this experiment was the effect of camouflage offset waveform on the Trial Type × Display Size interaction. This three-way interaction did not attain significance, $F(2, 36) = 0.4$, $MS_e = 278$. In agreement with this result, the Camouflage Waveform × Display Size interaction also failed to reach significance, $F(1, 18) = 0.1$, $MS_e = 261$. Thus the abrupt-capture effect seen in Experiment 1 was uninfluenced by whether the camouflage was removed gradually or all at once.

The Camouflage Waveform × Trial Type interaction, however, did attain significance, $F(2, 36) = 4.65$, $MS_e = 515$, $p < .05$; the relative positions of the three trial type functions in the two panels of Figure 5 depend upon the offset waveform. In particular, although there was a general increase in latency with abrupt camouflage removal compared to gradual removal (as revealed by the main effect of camouflage waveform), the no-onset function climbed more than the onset function did; this suggests that gradual removal did give subjects some usable preview infor-

mation. Nevertheless, abrupt onset targets were always detected more rapidly.

An inspection of Figure 5 will confirm that both abrupt and gradual Camouflage removal produced the effect seen in Experiment 1: In both cases, we observed a negligible display size effect for onset targets and a larger one for no-onset targets. The slopes for the Day 2 onset, no-onset, and negative conditions, respectively, were 9, 12, and 27 ms/item for gradual camouflage removal, and 7, 14, and 25 ms/item for abrupt camouflage
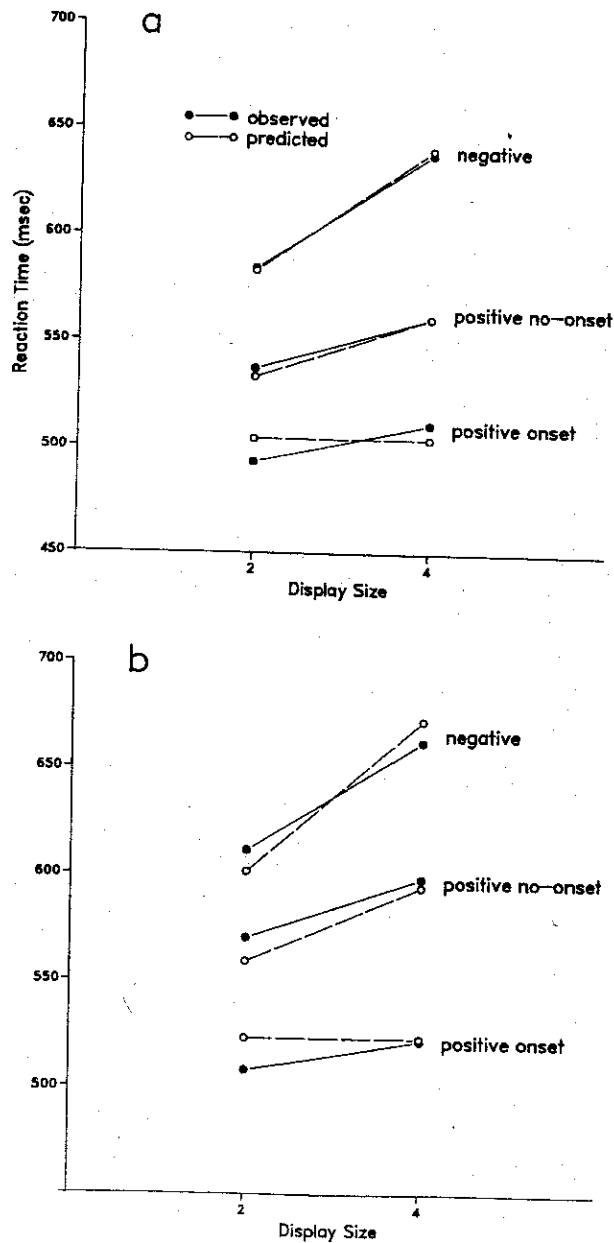

Figure 5. Mean reaction time on Day 2 as a function of display size. (Curve parameter is trial type. Panel a: gradual camouflage removal. Panel b: abrupt camouflage removal.)

Table 6

Parameter Estimates for Serial Capture Model, Experiments 1 and 3

Dataset	$\hat{\alpha}$	$\hat{\tau}$	$\hat{\nu}$	R^2
Experiment 1	412	38.1	33.2	.987
Experiment 3				
Gradual removal	475	28.8	50.3	.987
Abrupt removal	488	35.4	42.5	.965

removal. Bonferroni multiple contrasts confirmed that the onset slopes in each camouflage waveform condition were not significantly larger than zero ($p > .05$). Although no-onset slopes were significantly larger than zero ($p < .01$), they were not significantly larger than the onset slopes ($p > .05$), in contrast to the findings of Experiment 1. Finally, there was a significant difference between no-onset and negative slopes and between onset and negative slopes ($p < .01$).

The data were fit to the serial abrupt-capture model described in Experiment 1. The predicted means are illustrated in Figure 5. Table 6 summarizes the resulting parameter estimates, along with those from Experiment 1 for comparison. The model accounts for 98.7% and 96.5% of the variance in the means for the gradual and abrupt camouflage-waveform conditions, respectively. *RMS* error in the mean data was 5.4 ms and 9.8 ms for the gradual and abrupt waveform conditions, respectively; these values are less than 2% of the mean response times. Individual fits for each subject yielded median proportions of variance accounted for by the model within each subject of .923 (range: .68–.99) and .884 (range: .65–.99) for graudal and abrupt camouflage removal conditions, respectively. The parameter estimates were again reasonable;

for instance, the median τ obtained was 32 ms/comparison (range: 8–69). The fits are satisfactory and the parameter estimates are in rough agreement with those from Experiment 1.

We once again fit to the data the four alternative models described in the Appendix. Table 7 summarizes the goodness of fit for the data from Experiments 1 and 3 for the serial abrupt-capture model as well as for the four alternatives. Again, the serial, abrupt-capture model prevails. As in Experiment 1, the parallel, limited capacity, capture model was fit quite well. However, because the no-onset and negative slopes were significantly different ($p < .01$)—a violation of the parallel model's predictions—the serial, abrupt-capture model is preferred.

These results indicate that our precaution of removing the camouflage gradually in Experiment 1 was not crucial to the outcome of the experiment. At least in the context of this study, the presence of several abrupt offsets (sometimes as many as two complete figure eights) did not dramatically disrupt the apparent attention-capturing property of a single abrupt onset. This is consistent with Todd and Van Gelder's (1979, Experiment 2) finding that with stimulus–response uncertainty held constant, increasing the number of abrupt offsets in a display does not interfere with responses to remaining items.

One inconsistency between Experiments 1 and 3 remains: The Bonferroni contrasts showed that in Experiment 1, no-onset slopes were significantly larger than onset slopes, whereas in Experiment 3, the two were not statistically distinguishable. This result may be accounted for by the fact that the search rate τ for subjects in Experiment 1 (38.1 ms/

Table 7

Goodness of Fit for Alternative Models, Experiments 1 and 3

Experiment	Serial capture		Parallel limited		Parallel unlimited		Parallel re-search		Standard serial	
	R^2	*RMSE*	R^2	*RMSE*	R^2	*RMSE*	R^2	*RMSE*	R^2	*RMSE*
1	.987	5.9	.985	6.3	.761	25.1	.895	18.8	.772	24.5
3										
G	.987	5.4	.965	8.9	.862	17.6	.954	10.2	.843	18.8
A	.965	9.8	.961	10.1	.893	16.7	.885	17.5	.684	29.0

Note. RMSE = root mean squared error; G = gradual camouflage removal; A = abrupt camouflage removal.

comparison) was somewhat slower than that for subjects in Experiment 3 (28.8 and 35.4 ms/comparison). The more rapid search rates observed in Experiment 3 may have rendered true differences between the two slopes undetectable. The satisfactory model fits we have observed throughout support this view.

General Discussion

The results of these experiments are well described by the abrupt-capture model outlined at the end of Experiment 1: On every trial of visual search, attention is rapidly assigned to the channel containing the abrupt item. A comparison is made with the target item residing in memory, and on a match, a positive response is emitted; on a mismatch, the search continues in the standard serial self-terminating fashion. In Experiment 2, we tested and rejected the possibility that subjects could more easily process the onset items than the no-onset items due to some physical difference between the two. In that experiment, when attention was appropriately allocated in advance, there was no difference in detection latency. Finally, in the third experiment, we established that the no-onset procedure of Todd and Van Gelder (1979) is effective whether or not camouflage is removed gradually.

A consistent finding in both Experiments 1 and 3 was not predicted by the abrupt-capture model. In all three replications, we observed small positive slopes in the abrupt-onset conditions, where a slope of zero was predicted. A possible explanation for this result[9] is that attention is captured on *almost* all of the trials, but on some small proportion p of the trials, capture is not effective, and a serial search of the entire display ensues. In Experiment 1, for instance, p was estimated at about 10%. The addition of this parameter, however, improved R^2 from .987 to only .989, hardly justifying its inclusion in the model. Nevertheless, this mixture assumption appears to give a reasonable post hoc account of the otherwise unpredicted nonzero abrupt onset slopes.

It is important to remark that the occurrence of an abrupt onset does not by itself constitute a sufficient stimulus for capturing attention. Almost all experiments involving the presentation of visual stimuli, and in particular nearly all the visual search experiments conducted over the last decade and a half, involved *only* stimuli with abrupt onsets. Because we know that attention cannot be simultaneously committed to multiple noncontiguous spatial channels (Hoffman & Nelson, 1981; Posner et al., 1980), then clearly attention cannot be summoned to all abrupt visual events at once. Apparently only when the visual field contains but one such event (as when a relatively static scene is viewed and a moving object appears in the visual periphery) can attention be engaged in the manner illustrated by these experiments.

A demonstration of this idea was reported recently by Kahneman, Treisman, and Burkell (1983). Subjects in these experiments were asked to read or to detect the presence of words appearing at spatially uncertain locations in the visual field. In some conditions, the relevant stimulus appeared alone, and in others it appeared simultaneously with irrelevant and highly discriminable distractors. Kahneman et al. found that even when the distractors were patches of random dots with almost no features in common with the target word, subjects were significantly slower in naming the word as compared to conditions in which the word appeared alone. We interpret this as representing attentional capture by the single item, an event that is impossible when more than one abrupt onset occurs. This view is supported by the results of Experiment 5 by Kahneman et al. (1983), in which distractor elements were presented at various asynchronies with respect to the target word. When either an abrupt onset or an abrupt offset occurred simultaneously with target onset, response latencies were significantly slower than in a target-alone condition. In contrast, continuously present distractors or distractors removed well in advance of target onset resulted in RTs as fast or faster than those in the target-only condition.[10]

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[9] We thank J. E. K. Smith for this idea.

[10] This finding is somewhat inconsistent with the results of Experiment 3, which indicated that abrupt offsets did not interfere with capture by abrupt onsets. However, because the Kahneman et al. (1983) experiment included some conditions that are not analogous to any in the present experiments, direct comparisons may not be appropriate.

Another illustration of this point is found in an experiment by Kowler and Sperling (1983). Subjects were shown a series of 5 × 5 character arrays, one of which contained 23 letters, one digit, and a central fixation point; the rest consisted of 24 letters and a fixation point. Their task was to identify and locate the digit. Each array was presented in one of several ways: either with abrupt onset and ramped offset, ramped onset and abrupt offset, or abrupt onset and offset. Note that in contrast to the present experiments, the entire array followed a single temporal course. In this respect, the Kowler and Sperling procedure is similar to that employed by Breitmeyer and Julesz (1975). Kowler and Sperling found no enhancement or benefit of any kind for abruptly presented arrays over those presented gradually. This study was designed to determine whether the abrupt changes in retinal projection due to saccadic eye movements might functionally enhance processing of a newly fixated scene. Kowler and Sperling concluded that they do not. This is consistent with the hypothesis advanced in this article that *isolated* abrupt onsets capture attention. If all onsets, regardless of context, enhanced visual processing, the attentional capture explanation for the current results would be without merit, and an alternative model would be required.

One such alternative to be considered is Krumhansl's (1982) enhanced encoding model that we described earlier. This model does not employ the concept of attention, nor does it use the sensitivity of transient channels to abrupt onset or change. The critical property of Krumhansl's model is the initiation of a phase of rapid encoding at stimulus onset that gradually changes to a period of less rapid processing as the stimulus remains in view. This model described Krumhansl's data quite well. But although it does predict a difference between the onset and the no-onset conditions, it has no provision for the observed difference in the display size effects because stimulus encoding in the model occurs in all locations simultaneously and in parallel. Thus Krumhansl's model cannot as it stands account for the present data (although it could be expanded to do so; C. L. Krumhansl, personal communication, 16 January 1984). Some appeal

to attention (scarce resources, a limited capacity processing mechanism) seems required by the data reported here.

The current model would account for Krumhansl's data in the following manner. Initially, attention is evenly distributed over the prestimulus array. When the prestimulus array disappears, the subject must localize and identify the remaining stimulus. If the remaining object is of the form-change type and therefore exhibits an abrupt change at trial onset, attention is immediately secured by the appropriate input channel, and the required processes may proceed at once with their tasks. In contrast, when the remaining object does not contain an abrupt change at trial onset, there is no attentional imperative "marking" the relevant channel. Thus time must be occupied with a rather slower localization process (which frequently is not complete at mask onset) before stimulus identification can commence.

On the current model, an abrupt onset among gradual ones has an attentional status similar to that of an *X* among *O*s (Treisman & Gelade, 1980) or a digit among letters (Egeth et al., 1972). That is, it is a perceptual feature of the stimulus that can be "encoded" at some early level of the visual system in parallel and without restriction across the entire field and that can then be used as a basis for passing the associated stimulus into a limited-capacity system (Duncan, 1980). In our view, the abrupt onset differs from these other stimulus properties (e.g., shape, category) in that it is an imperative; it summons attention (in Duncan's terms, it requires immediate passage into the limited-capacity system), perhaps without intention, effort, or awareness on the subject's part. These are some of the commonly held criteria for processing automaticity (Posner & Snyder, 1975; Schneider & Shiffrin, 1977).

Some predictions of this model may make it more concrete. One is that with brief exposures, objects spatially adjacent to the abrupt object should be processed more efficiently than those farther from it (cf. Hoffman & Nelson, 1981). Other predictions have to do with the involuntary nature of automaticity: If a subject is asked to attend to a particular spatial location (e.g., Eriksen & Hoffman, 1973) and if that location contains

a target, then we would expect that an abrupt nontarget in some other location would be more likely to interfere with target processing than a no-onset nontarget would. Conversely, if an unattended object is the target, we would expect performance to be nevertheless quite good if it has an abrupt onset. In other words, objects with abrupt onsets should be efficiently processed regardless of the subject's intentional allocation of attention. These predictions hold only, of course, if there is at most one abrupt item in each display.

A finding of Todd and Van Gelder (1979) that is also predicted by this model involves the increased complexity of the task required of subjects across experiments from one of simple detection to more difficult letter discrimination. The relative advantage of onset over no-onset presentation increased with complexity. This is consistent with the finding (Shaw, 1984) that letter discrimination cannot be accomplished with divided attention, whereas simple luminance increment detection can be. If abrupt onsets capture attention, the observed effects of such capture would be expected to be greatest when attention is most needed. This is just what Todd and Van Gelder (1979) observed.

Conclusion

We have shown in these experiments that isolated abrupt onsets are rapidly detected in visual search, and we have offered an attentional capture model that satisfactorily accounts for the data. The model provides for the immediate recruitment of attentional resources by visual channels containing signals with abrupt onsets.

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Appendix

Description of the Alternative Models

A brief description of the four alternative models we tested is given here. Theoretical predictions for these models, as well as for the serial abrupt capture model described in the text, are shown in Figure A1. All of these predictions are based on varying the definition of k in Equation 1, while leaving its other terms intact.

1. *Parallel, limited capacity abrupt-capture model.* As Atkinson et al. (1969) and Townsend

Figure A1. Theoretical predictions of the five alternative models considered in this article. (For convenience, we have set $v = \tau$. Panel a: serial abrupt capture. Panel b: parallel, limited capacity capture. Panel c: parallel, unlimited capacity capture. Panel d: parallel, unlimited capacity re-search capture. Panel e: standard, serial, self-terminating. A = abrupt onset, G = gradual no-onset, N = negative.)

(1972) have pointed out, a parallel process can perfectly mimic a serial process, with the inclusion of certain assumptions. For instance, a parallel process can produce the display size effect—which is the paradigmatic case of a serial process—if it is assumed that (a) processing resources are limited, (b) processing rate is directly proportional to the amount of available processing resources, and (c) as each item is identified, the rate of processing for all unfinished items increases as limited processing resources become available. Thus, as the number of nontarget items in the display increases, the expected response latency also increases, because available resources for any one item (and hence processing rate) are declining.

We instantiated the parallel mimic by assuming that the abrupt onset item, as in the serial capture model, summons attention and is processed first. If the abrupt item is not the target, all other items in the array are scanned in parallel, with processing rate inversely proportional to the number of remaining items. No-onset and negative slopes are therefore predicted to be equal. Referring to Equation 1, when the target is the abrupt onset item, $k = 1$; otherwise, $k = d$.

2. *Parallel, unlimited capacity capture model.* This model assumes that the onset item is processed first, and if it is not the target, all other items are processed in parallel with processing rate independent of display size. Here, $k = 1$ when the abrupt item is the target and $k = 2$ otherwise. This model predicts zero slopes for all three trial types, with intercept differences of τ between the onset and no-onset funtions and v between the gradual and negative functions.

3. *Parallel, unlimited capacity re-search capture model.* In order to produce nonzero slopes for the negative trials, we evaluated a model identical to Model 2 with the added assumption that a serial re-search of the display occurs on negative trials. Under this model, k is as in Model 2 except on negative trials, when $k = 2 + d$.

4. *Standard serial model.* This model assumes that all the items in the display are treated identically, so the onset and no-onset data are predicted to be the same. A serial, self-terminating search predicts a positive slope that is one half the magnitude of the negative slope. In terms of Equation 1, $k = (d + 1)/2$ on positive tr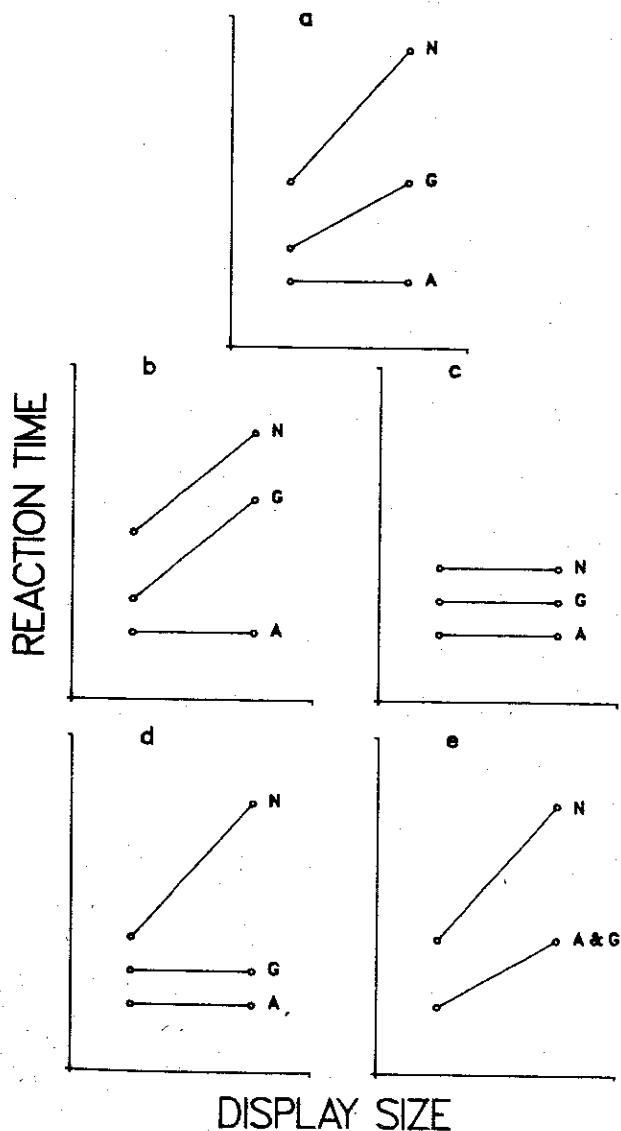ials and $k = d$ on negative trials.