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Visual Attention and Stimulus Identification

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Previous research has provided evidence for parallel stimulus processing in visual search tasks; however, it has frequently been noted that detecting prespecified targets might be accomplished without actually identifying targets and/or distractors. A novel task was employed to require exhaustive identification: Subjects named the highest digit in an array. Reaction times and display size effects in this task were strikingly similar to the conventional search tasks reported here. Manipulation of display size and visual quality was used to test predictions of serial versus parallel encoding models. Display size was additive with two different visual quality factors in the highest digit task, a finding that argues against serial execution of the corresponding stages. Interactions with decision-related factors suggest that visual quality may have affected the rate of character recognition, not just feature extraction. Thus, various aspects of the results seem to strengthen the case for parallel (though perhaps capacity-limited) identification of multiple familiar stimuli. In the General Discussion, it is pointed out that parallel identification need not entail late selection, and some alternative possibilities are suggested.

A very basic question about human visual information processing mechanisms is whether recognition of familiar objects requires some kind of a serial attentional scan. Arguments against this requirement have commonly been presented in the context of strong *late-selection* theories (e.g., Duncan, 1980b; Shiffrin, 1976). According to these theories, selection of stimuli for response occurs after a process of pattern recognition has been applied unselectively and without capacity limitations, creating a representation that combines object identities with other features capable of serving as selection criteria, such as spatial location. Clearly, parallel pattern recognition might be available to the system even if these very strong mechanisms postulated by late-selection theory were not present: Stimulus identification may sometimes occur in parallel, but not necessarily unselectively or without capacity limitations (an issue we will turn to in the General Discussion). The major alternative position is generally termed *early selection* to indicate the view that selection, on the basis of criteria like spatial location, precedes identification. Despite the considerable amount of research investigating these issues, substantial disagreement remains (see, for instance, Posner, 1982, on one side; Kahneman & Treisman, 1984, and Broadbent, 1982, on the other).

The question of whether multiple familiar patterns can be recognized simultaneously has been investigated through a wide variety

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of methods. The most direct approach would seem to be the whole-report paradigm, in which the subject is required to report as many items as possible from a briefly presented display. Although this technique has produced a number of very interesting results, it has become clear that performance reflects postperceptual limitations as well as limitations on the encoding process itself (see Estes, 1978, for a review). Some investigators continue to attempt to disentangle these factors through more sophisticated analyses (Townsend & Ashby, 1984; Wolford, 1975), but such efforts have proven to be difficult. Similarly, the partial-report paradigm (Sperling, 1960) has provided useful information on the time-course of visual persistence, but studies attempting to distinguish serial from parallel identification with this technique have appeared quite inconclusive (see Duncan, 1981).

Evidence for Parallel Encoding

The introduction of visual search paradigms (Estes & Taylor, 1964) has been extremely useful in examining multielement pattern recognition while minimizing the role of postperceptual limitations. In these experiments, subjects indicate whether or not a particular target or targets were present (or in some cases, which of two targets was present) in a multielement display. The general finding is that reaction times (RTs) are longer and accuracy poorer as display size is increased. This might be due to limitations on encoding, limitations on subsequent stages (e.g., memory comparison), and/or statistical factors (i.e., increase in chance of error with more comparisons; see Duncan, 1980a). A number of methods designed to disentangle these factors have provided strong evidence for parallel encoding of multielement displays. Shiffrin & Gardner (1972) required subjects to determine which of two targets was present in a display of four items, which was followed by masks, impairing accuracy. Performance was assessed when items were exposed in successive pairs, each for a particular duration, and also when the entire display was exposed simultaneously for that same duration. The simultaneous condition did not produce inferior performance, suggesting that the efficiency of encoding was not reduced by the need to encode all items at the same time.

Van der Heijden (1975) examined performance in a consistent-mapping visual search while manipulating display size and presence of redundant targets. Various workers have observed facilitation from redundant targets, but Van der Heijden reported a more decisive finding: Subjects were faster to detect targets in three-item displays in which all items were targets than in a display of two items which were all targets, and so on. It is difficult to reconcile this result with a serial search process, but it fits well with the predictions of various parallel self-terminating models.

Finally, the slope relating RTs to display size has been observed to be quite flat under certain circumstances. In particular, search for letters among digits may show such an effect (Egeth, Jonides, & Wall, 1972), as may search for arbitrary target sets following extensive consistent practice (Schneider & Shiffrin, 1977).

Alternative Interpretations

These various results seem to indicate that character detection is not performed on the basis of a serial encoding process. However, the simplicity that is a virtue of detection paradigms may also be seen as something of a limitation. Accurate detection of a target among distractors indicates successful discrimination of a prespecified item from the background items, but it is far from obvious that it indicates *identification* of either target or distractor items in the display. This distinction is sometimes obscured by the imprecise use of the term *encoding.* The uncertainty concerning the nature of the information underlying detection performance has been the basis for a number of major criticisms of the parallel-identification interpretation of detection paradigms.

Eriksen and Collins (1969) presented evidence to support the hypothesis that search may depend upon nothing more than a filter-like process that can "screen out the noise stimuli" (p. 489). They compared performance in two tasks involving digits presented successively in numerical order: Subjects were required to report the presence or absence of a specified digit in the sequence, when that digit was specified either before or after the presentation of the sequence. Subjects required almost three times as long an exposure of each item in the second task to achieve comparable performance. The authors concluded that identification required much more stimulus processing than is necessary for target-detection. As Eriksen and Collins acknowledge, however, their second task may differ from the first not only in demanding identification of each element but also in making greater demands on memory and/or decision processes.

A similar idea was proposed by Hoffman (1978, 1979), who developed an interesting model of visual search in which character detection is based upon a parallel process that merely computes the overall similarity of each item in the display to the desired target. This parallel process is held to be error prone and must be followed by a checking stage that focuses upon the most likely candidate target in the display. Along similar lines, Rabbitt (1978) criticized the widespread tendency to equate the rejection of a distractor in search with the identification of that distractor. Closely related points have been made by writers pointing out possible differences between encoding processes underlying whole-report and detection tasks (Townsend & Ashby, 1984; Wolford, 1975). Wolford proposed a visual information processing model involving a serial encoder, which could proceed through the display at a rate dependent upon the number of discriminations necessary; he suggested that this would be high in full report and low in search. The doubts about search methodologies raised by Eriksen and Collins, Hoffman, Rabbitt, and others seem entirely cogent, and it does not seem that they can be dismissed on the basis of existing empirical work.

A related conjecture was raised by Treisman and Gelade (1980). These authors suggest that the parallel analysis of visual information may be restricted to the extraction of relatively simple visual features, such as color or basic elements of form. The process of accurately conjoining the features present in particular objects may, according to these authors, require a serial deployment of focal visual attention. In the absence of visual attention, perception may occur without guarantee of accurate feature conjunction. Treisman and Gelade performed a number of search experiments in which targets and distractors were composed of a common set of features, requiring accurate feature conjunction for successful discrimination. Their findings were suggestive of a serial self-terminating search, which they interpreted as indicating a serial encoding process. They suggested that the experiments indicating unlimited encoding capacity (e.g., Shiffrin & Gardner, 1972) may have required only discriminations that could be performed on the basis of *featural* analysis alone. Thus, in some sense, Treisman and colleagues follow Eriksen and Collins, Rabbitt, Hoffman, and others in questioning whether evidence for parallel encoding in ordinary detection experiments really indicates that full-scale pattern recognition can occur in parallel.

Present Research

The present article reports a series of experiments that attempt to address the weakness of search methodologies pointed out by the above authors. We do this by employing a new task designed to require full identification of multiple characters: Subjects must name the highest of an array of digits. In addition to the requirement of exhaustive identification, this task would seem to involve a decision stage of much greater complexity than that required for simple search tasks. Surprisingly, as will be reported below, performance in this task is very similar to that typically observed in character search, both in terms of overall RTs and the effects of display size.

The present work will also try to shed some light on the hypothesis of parallel stimulus identification, using an experimental design that offers a tool for distinguishing parallel from serial encoding. The basic idea is very simple. Suppose the experimenter manipulates both the size of a display and the time required to encode each stimulus (through visual quality changes). If the subject performs the task by serially encoding each item in the display, then the effect of display size should interact in a multiplicative fashion with the visual quality manipulation. Basically, the visual quality effect on the encoding of *each* item would be added to the overall RT, once for each additional item in the display (presuming exhaustive processing). Alternatively, suppose that the encoding proceeds in parallel; plainly, the visual quality effect should be basically additive with the display size.[1] Thus, these alternative models produce *highly* divergent predictions, which one might expect to be readily testable.

Two studies of this type have been reported in the literature. Johnsen and Briggs (1973) had subjects search for two or four targets in displays of one to four items, in varied or continuous mapping conditions. Visual quality was manipulated by superimposing visual noise on the display, producing a very large (345 ms) effect. With the exception of a small interaction in one condition *(no* trials; fixed mapping), the display size and noise combined *additively,* while noise interacted with target presence/absence. Logan (1978; Experiment 4) had subjects search displays of 4-12 items in forced-choice detection; the effect of a noise manipulation (much smaller than Johnsen and Briggs') was very closely additive with display size. Using additive factors reasoning, the authors of these studies interpreted their results as indicating that display size and visual quality affect *different stages* of processing. Surprisingly, they did not remark upon the implications for possible serial encoding models, and the various citations to this finding that we have located in the literature have not commented upon this implication either. This may indicate the widespread assumption of parallel encoding, rather than any oversight. In any case, the results seem to provide converging evidence with the findings of Shiffrin and Gardner (1972), Van der Heijden (1975), Duncan (1980b), and others who have argued for parallel encoding processes in search.

Five experiments will be reported below. The first two involve "standard" character search, and the last three involve the highest digit task mentioned above. In all the experiments, two factors are manipulated: the size of the display (two, four, and six elements), and the visual quality of the whole display. The central questions of interest concern (a) the overall performance in the highest digit task (i.e., slopes and RTs) compared with typical search performance and (b) the additivity or interaction of display size and visual quality in the different tasks.

Experiment 1

The first experiment was intended to replicate the Johnsen and Briggs' (1973) finding (additivity of display size and visual quality), using a somewhat different quality manipulation and a consistent-mapping search for a single target. In the experiments reported in this article, contrast reduction was accomplished by reducing the intensity of letters by presenting them in the dark-gray color available on the microcomputer used for experiment control, as opposed to the white color used for the high-intensity condition. This produced a modest but consistent contrast effect. Subjects searched for the single target letter *A* in displays of two, four, or six characters. The entire display was either high or low contrast, and both manipulations (display size and contrast) were presented in mixed trials to prevent subjects from anticipating the level of the manipulations.

Method

Subjects. Twelve University of Pennsylvania students served as subjects in a 1-hr session in return for payment.

Stimuli and design. The uppercase letter *A* was always the target, while the next 19 uppercase letters of the alphabet served as distractors. Letters were composed from a 7 by 7 dot grid, measuring .5 cm width by .7 cm height. Displays of two elements were positioned on a line 5.1 cm in length. Displays of four elements were positioned as corners of a rectangle 5.1 cm by 2.1 cm. The display of six items occupied these four positions and two more which were located directly above and below the fixation point (total dimensions were 5.1 cm by 3.7 cm). The outer dimensions of the six-item display represented about 4.9° horizontal visual angle by 3.5° vertical visual angle, based on a typical viewing distance of 60 cm. This arrangement of fixed display positions for each display size minimized the confounding of display size with positional uncertainty. The elliptical shape held acuity roughly constant across display positions.

The experiment was divided into 10 blocks of 60 trials.

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[1] If quality increases the variability of encoding durations (all operating in parallel), then responses that depend upon completion of encoding all items (presumably on target-absent trials) should show larger quality effects with larger displays. However, the magnitude of the interaction this predicts is very small, given modest effects on variability, and it should not be surprising if it is not detectable.

In each block, 5 trials appeared in each Display Size X Visual Quality X Target Presence/Absence cell. The distractors were chosen at random without constraint, and the position of the target, when present in the display, was selected randomly.

Procedure. The stimuli were presented on an Amdek Color-I monitor, controlled by a Commodore microcomputer. A centrally positioned warning signal (plus sign) appeared on the screen for 750 ms. Upon its offset, the display appeared, remaining on the screen for 100 ms. Subjects were instructed to respond as quickly as possible, while maintaining good accuracy. Their responses were made by pressing one of two switches on a panel resting on the table in front of them. The switches were easily depressed by pushing one of two 1.6-cm diameter plastic buttons located 10 cm apart on the panel. Half the subjects used their right-hand index finger for target presence and the left-hand index finger for target absence; for the other half of the subjects the assignment was reversed. The interval between response and the beginning of the following trial was approximately 2.1 s. The experiment began with one practice block, which was not analyzed. Subjects were presented cumulative feedback after each block, consisting of their average RT and total number of errors for the current block and each preceding block. These interblock periods constituted a rest period, which was terminated by the subject when ready. Timing of responses was controlled by the microcomputer, using machine language routines adapted from Merikle, Cheesman, and Bray (1982). These routines utilize on-board microsecond clocks and permit synchrony of response timing with display onset.

Results

RTs less than 150 ms or in excess of 1,500 ms were discarded. The average correct RTs are presented in Figure 1, and the error rates are presented in Table 1. As the figure indicates, the effects of display size and visual quality were basically additive. Collapsed over *yes/no* factor, the visual quality effects were 35, 43, and 40 ms, for display sizes of two, four, and six items, respectively. The effect of quality was significant, *F*(1, 11) = 43.5, *p* < .0001, as was the display size effect, *F*(2, 22) = 53.2, *p* < .0001. Their interaction failed to occur significantly, *F*(2, 22) < 1. The effect of quality averaged 51 ms for *no* trials and 28 for *yes* trials. The *yes/no* effect was significant, *F*(l, 11) = 58.9, *p* < .0001, and it interacted significantly with visual quality, F(1, 11) = 11.14, *p* < .01. The interaction of yes/no with display size was significant, *F*(2, 22) = 4.92, *p* < .02, but the Quality X Yes/No X Display Size interaction showed no sign of significance, *F*(2, 22) < 1.

The error rates were analyzed likewise. The effect of quality was significant, *F*(1, 11) =6.73, *p* < .05, along with the display size effect, *F*(2, 22) = 8.07, *p* < .005, and the interaction of display size with quality, *F*(2, 22) = 6.98, *p* < .01. The effects of yes/no failed to reach significance, *F*(1, 11) < 1, as did other interaction terms.

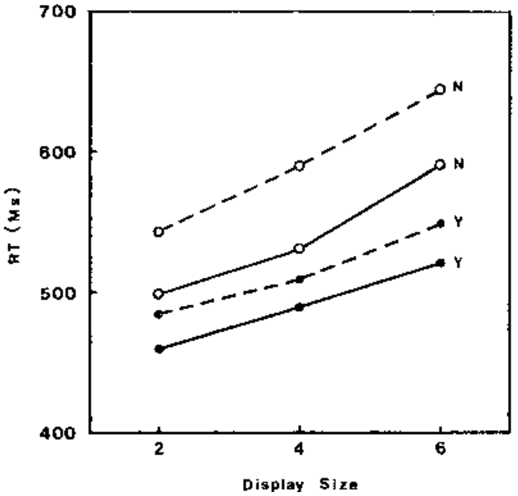

Figure 1. Mean reaction times (RTs) in milliseconds (ms) as a function of display size in Experiment 1—character search. (Solid lines = high intensity; broken lines = low intensity; filled circles = target present [Y]; open circles = target absent [N].)

Experiment 2

Experiment 1 replicated the Johnsen and Briggs (1973) findings of additivity of display size and visual quality, together with an increased visual quality effect for *no* responses, in a consistent-mapping character search. This finding suggests that the encoding processes retarded by intensity reduction in this task proceed in parallel, converging with earlier results involving different paradigms (Shiffrin & Gardner, 1972). It has been pointed out by Treisman and Gelade (1980) that ordinary character search tasks might be performed on the basis of detecting a single feature. These authors suggested that serial scanning will be necessary whenever the target in a search task can be constructed out of rearrangements of the features composing the distractors, thereby requiring accurate feature conjunction (henceforth, the PIC condition, for *potential illusory conjunctions).* The present experiment, therefore, employed a target/

Table 1
Error Rates (%): *Experiment 1*

Condition	Display size 2	4	6
High quality			
Target present	1.6	3.0	3.0
Target absent	2.0	1.5	2.0
Low quality			
Target present	2.5	5.8	9.2
Target absent	2.5	6.0	10.5

distractor combination specifically mentioned by Treisman and Gelade as a PIC condition, namely the target *E* among distractors *F* and *L;* in the character set used here, there was complete spatial overlap when these characters were superimposed. If the feature conjunction view is correct and if the sequential processes posited by the model are retarded by stimulus intensity, then one would expect to find over-additivity of quality with display size, when this target/distractor set is used.

Method

Subjects. Twelve University of Pennsylvania students served as subjects in a 1-hr session in return for payment.

Stimuli and design. The letter *E* was always the target, while the letters *L* and *F* served as distractors. Distractors were chosen randomly with replacement. The characters were composed of a 7 by 7 dot grid, measuring 0.7 cm in height and 0.5 cm in width. Items in the display were arrayed in a circle about the center of the screen, in positions corresponding to 12, 2, 4, 6, 8, and 10 hr on a clock face. The width of the display was 3.9 cm, and the height of the display was 3.7 cm. When the display consisted of two items, they were opposite each other along a randomly chosen axis. Displays of four items occupied positions along two randomly chosen axes. Based on a typical viewing distance of approximately 60 cm, the display measured about 3.7° by 3.5° visual angle in width and height, respectively.

The experiment was divided into 10 blocks of 60 trials. In each block, 5 trials appeared in each Display Size X Visual Quality X Target Present/Absent Cell. The distractors were chosen randomly from the set of two without constraint, and the position of the target, when present in the display, was also selected randomly.

Procedure. The procedure basically followed that of Experiment 1, but in order to better approximate the procedures employed in Treisman and Gelade's experiments, the displays remained on the screen until response execution (rather than 100 ms, as in Experiment 1).

Results

RTs less than 150 ms or greater than 1,500 ms were discarded. The average correct RTs are presented in Figure 2, and the error rates are presented in Table 2. As the figure indicates, the effects of display size and visual quality were basically additive, as in Experiment 1. The effect of quality was significant, $F(1, 11) = 34.9$, $p < .0002$, as was the effect of display size, $F(2, 22) = 92.7$, $p < .0001$. Their interaction was nonsignificant, $F(2, 22) < 1$. The target presence/absence effect was significant, $F(1, 11) = 99.9$, $p < .0001$. It interacted significantly with quality, $F(1, 11) = 17.5$, $p < .002$, and with display size, $F(2, 22) = 7.33$, $p < .0036$. The Quality X Display Size X Target Presence/Absence interaction was nonsignificant, $F(2, 22) < 1$.

The errors were analyzed likewise. The factor effects were not significant, in particular, quality, $F(1, 11) = 3.01$, $p > .10$, display

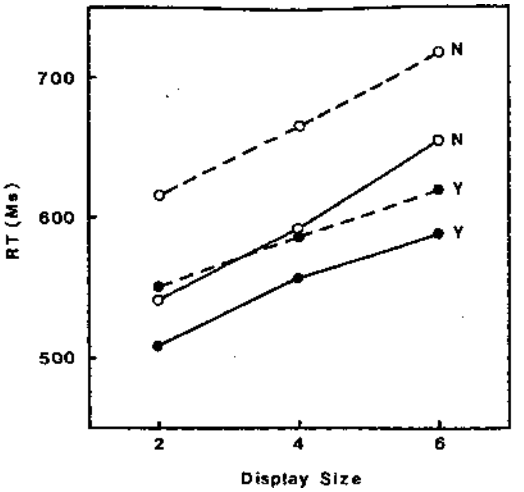

Figure 2. Mean reaction times (RTs) in milliseconds (ms) as a function of display size in Experiment 2—character search, (Solid lines = high intensity; broken lines = low intensity; filled circles = target present [Y]; open circles = target absent [N].)

Table 2
Error Rates (%): Experiment 2

Condition	Display size 2	4	6
High quality			
Target present	1.2	1.6	2.1
Target absent	2.0	2.1	2.0
Low quality			
Target present	2.3	2.0	2.1
Target absent	1.5	2.3	3.3

size, $F(2, 22) = 1.17$, $p > .30$, and target presence/absence, $F(2, 22) < 1$. The interaction of display size by quality was nonsignificant, $F(2, 22) = <1$, as were the other interaction terms.

Discussion: Experiments 1 and 2

The present experiments replicate the findings of Johnsen and Briggs (1973) in two character search experiments. In the second, the target and distractors overlapped in component features so as to require correct feature conjunction (PIC condition), and thus, on the theory of Treisman and Gelade (1980), a serial attentional scan. A serial self-terminating model of the detection process (Treisman & Gelade, 1980) is not supported by the present slopes; the ratio of display size slopes for target-absent to target-present trials is about 1.5:1, rather than the 2:1 ratio observed by Treisman and Gelade (and predicted by their model). One account of this discrepancy might be the very large displays used by those authors, with the likely involvement of eye movements.

The effect of visual quality was additive with display size, and was greater for *no* responses than *yes* responses in both experiments. By the reasoning described in the introduction, this additivity clearly suggests that the stage(s) retarded by the intensity reduction are not executed serially; otherwise, a multiplicative interaction would be expected. The question now becomes which stages of stimulus processing are in fact retarded. The interaction of quality with target presence/absence seems to speak against the possibility that these effects are limited to early feature-extraction (similar arguments on this point have been suggested by Miller, 1979). If this is correct, the data reject serial encoding hypotheses. A fuller discussion of these aspects of the data, and also the pattern of error rates, will be put off until the General Discussion.

Experiment 3

The results of Experiments 1 and 2 indicate that in a visual search task, the effects of stimulus intensity are additive with the effects of increasing the size of the display from two to six. The results replicate the findings of Johnsen and Briggs (1973), using a much smaller stimulus degradation manipulation than those writers employed. They also indicate that this additivity appears even when the distractors contain features that could potentially be recombined to form a (spurious) target (Treisman and Gelade, 1980). In view of these results and the finding of Logan (1978; Experiment 4) as well, this additivity seems to be a reasonably robust effect.

In the introduction, a major question was raised with respect to various interpretations of data obtained in search paradigms (e.g., Shiffrin & Gardner, 1972). Specifically, as a number of writers have suggested, the stimulus encoding process in visual search may involve something quite different from a full stimulus identification, such as would be required for report. Eriksen and Collins (1969), Rabbitt (1978), and Hoffman (1978, 1979) pointed out that the distractors in a visual search task might be rejected without deriving identity codes for them. Similar ideas have also appeared in discussions of differences between detection tasks and whole-report tasks (e.g., Townsend & Ashby, 1984; Wolford, 1975). Logically speaking, these suggestions seem cogent. Various devices used in electronic signal processing, for instance, can be said to detect a signal in noise without in any sense *recognizing* or encoding the elements composing the noise. Numerous investigations of attention, however, have utilized search paradigms with the underlying assumption that successful monitoring of several channels in auditory and visual search can be equated with identification of the contents of those channels (e.g., Shiffrin & Gardner, 1972; but see Gardner, 1972, p. 151). In short, it is possible that the simultaneous encoding argued for by the additivity of degradation and display sizes (and also the lack of evidence for attentional limits in paradigms like Shiffrin & Gardner's, 1972) might speak only to the capabilities of a process that detects prespecified targets and treats distractors as noise.

To test this conception, one requires a paradigm in which exhaustive *identification* of each item in the display is necessary for accurate response. The following experiments were designed with this in mind. Subjects were presented with an array of two, four, or six digits and were instructed to vocally name the numerically highest digit in the array.

The digits ranged from 0 to 7 (8 and 9 were highly confusable in the character set used). Targets ranged from 3 to 7, with equal probability, and the distractors were selected to range from zero up to the target. In this task, the subject clearly must encode the characters at a conceptual level, to appreciate their numerical significance. Furthermore, the process must usually be exhaustive; having identified a portion of the array, the subject could have no assurance that a remaining digit will not be higher than the current highest. (The only exception was the approximately 20% of trials on which the digit 7 was the highest.)

Method

Subjects. Fourteen University of Pennsylvania students served in a 1-hr paid session.

Stimuli and design. The digits composing each array were selected as follows. First, the highest digit was selected at random from the range 3 to 7. Then the remaining digits in the display were selected at random, without constraint, from the range 0 up to one less than the highest digit (thus there were no repetitions of the highest digit). The placement of the arrays on the screen exactly followed the procedure of Experiment 1; as in that experiment, the array positions were fixed for each display size. Each session was divided into 10 blocks of 60 trials each. Within each block, there were 10 trials in each Visual Quality X Display Size combination.

Procedure. The procedure largely followed that of Experiment 1. As in that experiment, displays were exposed for 100 ms. The latency of the subject's vocal responses was timed with a Grason-Stadler Model E7300A-1 Voice Operated Relay, connected to the Commodore microcomputer through the parallel input port. Four hundred ms after the subject had responded, the correct response appeared on the middle of the screen. The subject pressed the space key to indicate that he or she just made a correct response, and the (/) key to indicate an error. The importance of accurate self-scoring was emphasized to each subject. The interval between the scoring response and the fixation point for a new trial was about 2.5 s. The trial itself proceeded as in Experiment 1.

Results

Response times less than 150 ms or greater than 1,500 ms were discarded. The mean correct RTs for each condition are shown in Figure 3. The quality effects averaged 43, 53, and 46 ms, for display sizes of two, four, and six, respectively. The effect of quality was significant, $F(1, 13) = 65.4, p < .0001$, as was the effect of display size, $F(2, 6) = 91.7, p < .0001$. The Quality X Display Size interaction was nonsignificant, $F(2, 26) < 1$.

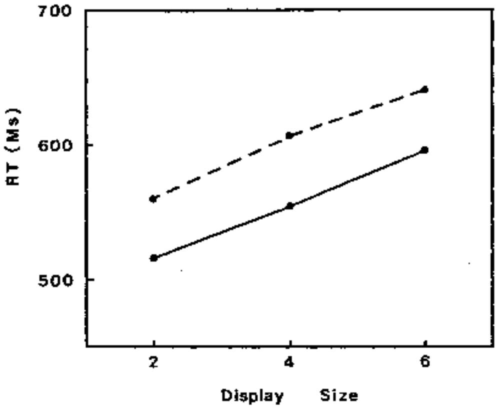

Figure 3. Mean reaction times (RTs) in milliseconds (ms) as a function of display size in Experiment 3—highest digit task. (Solid lines = high intensity; broken lines = low intensity.)

Error rates for high-quality displays were 0.4%, 2.1%, and 4.8% for display sizes of two, four, and six, respectively. Low-quality displays yielded error rates of 4.1%, 10.1%, and 13.4% for display sizes of two, four, and six, respectively. The effect of quality was significant, $F(1, 13) = 29.1, p < .0002$, as was the display size effect, $F(2, 26) = 24.9, p < .0001$. Their interaction was also significant, $F(2, 26) = 9.1, p < .005$.

Table 3 presents the mean reaction times and error rates as a function of the identity of the highest digit, collapsed across display size. The effect of digit on RTs was significant, $F(4, 52) = 12.9, p < .0001$, as was the effect of quality, $F(1, 13) = 58.1, p < .0001$. The Quality X Digit interaction was also significant, $F(4, 52) = 4.3, p < .01$. Inspection of Table 3 suggests that reaction times decrease as a function of the highest digit, with the exception of an increase when the digit is 6. This data point seems quite discrepant in both RTs and errors, both here and in the following experiment; we believe this is due to the poor quality of this character on our CRT display, particularly with low contrast. To examine the apparent downward slope of the function relating RT to highest digit, the data were reanalyzed, excluding highest digit 6. The effect of digit was significant, $F(3, 39) = 18.6, p < .0001$, as was the quality effect, $F(1, 13) = 36.1, p < .0001$. The trend toward interaction of digit and quality did not reach

Table 3
RTs and Error Rates (ER) by Highest Digit and Quality: Experiment 3

	High Quality		Low Quality	
Highest digit	RT	ER (%)	RT	ER (%)
3	576	3.4	638	12.5
4	570	2.0	610	4.9
5	551	0.8	594	4.6
6	545	3.9	614	19.6
7	533	2.1	560	4.7

significance, $F(3, 39) = 2.2$, $.10 < p < .15$.

Experiment 4

The fourth experiment was designed to assess the generality of the finding of Experiment 3, namely additivity of display size and stimulus quality in a task requiring subjects to name the highest digit in an array. In the present experiment, the displays remained on the screen until response, whereas the previous experiment employed brief displays. Brief displays prevent eye movements, but they lead to an overall reduction in accuracy.

Method

Subjects. Ten University of Pennsylvania students served as subjects in return for payment.

Stimuli and design. Stimulus selection and experimental design followed that of Experiment 3 exactly. Displays of two items were presented on a randomly chosen diagonal, one of the two composing the corner positions occupied by the displays of four elements.

Procedure. The procedure followed that of Experiment 3, except for a single change: The displays of digits remained on the screen until the computer detected a response.

Results

RTs less than 150 ms or greater than 1,500 ms were discarded. The average RTs in the six conditions are shown in Figure 4. The quality effects averaged 67 ms, 71 ms, and 79 ms for display sizes of two, four, and six, respectively. The effect of quality was significant, $F(1, 9) = 29.3$, $p < .0005$, as was the effect of display size, $F(2, 18) = 77.7$, $p < .0001$. The interaction was nonsignificant, $F(2, 18) < 1$.

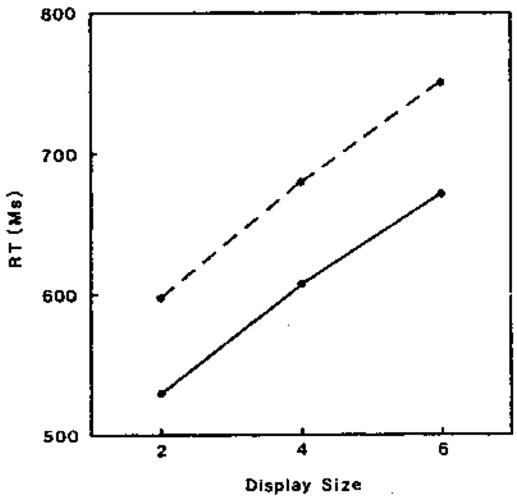

Figure 4. Mean reaction times (RTs) in milliseconds (ms) as a function of display size in Experiment 4—highest digit task. (Solid lines = high intensity; broken lines = low intensity.)

Error rates for high-quality displays were 0.9%, 2.5%, and 4.3% for display sizes of two, four, and six, respectively. Low-quality displays yielded error rates of 2.1%, 3.5%, and 6.0% for display sizes of two, four, and six, respectively. The effect of display size was significant, $F(2, 18) = 14.2$, $p < .0005$, but the effect of quality was not, $F(1, 9) = 3.6$, $.05 < p < .10$. The interaction was nonsignificant, $F(2, 18) < 1$.

Table 4 presents the mean reaction times and error rates as a function of the identity of the highest digit, collapsed across display size. The effect of digit was significant, $F(4, 36) = 21.4$, $p < .0001$, as was the effect of quality, $F(1, 9) = 27.0$, $p < .001$. The Quality X Digit interaction was also significant,

Table 4
RTs and Error Rates (ER) by Highest Digit and Quality: Experiment 4

Highest digit	High Quality		Low Quality	
	RT	ER(%)	RT	ER (%)
3	631	1.3	728	2.8
4	622	2.3	687	3.0
5	606	1.6	663	1.8
6	602	5.6	703	9.8
7	556	2.4	594	2.2

$F(4, 36) = 9.6, p < .0001$. As in Experiment 3, the data for highest digit 6 appeared anomalous (probably due to its poor discriminability in our character set); the data were reanalyzed without these trials. The effect of digit was significant, $F(3, 27) = 26.7, p < .0001$, as was the quality effect, $F(1, 9) = 22.8, p < .001$. In this experiment, the interaction of digit and quality reached significance, $F(3, 27) = 11.4, p < .0001$. Thus, the data indicate a reliable tendency for faster RTs and smaller quality effects, the higher the highest digit.

Experiment 5

The previous two experiments demonstrated additive effects of display size with a manipulation of the intensity of the display in a task requiring subjects to name the highest digit in an array. To explore the robustness of this effect, the present experiment examined effects of display size and the degradation of the display with a superimposed noise grid.

Method

Subjects. Thirteen University of Pennsylvania students served as subjects in return for payment.

Stimuli and design. Stimulus selection and experimental design followed that of Experiment 3. Digits were presented on the cathode-ray tube (CRT) screen as in that experiment (but with the digits in black on a white screen); here, a transparency affixed to the screen contained six dot patches in certain positions, which served as noise. Each digit in the degraded display appeared in one of these positions. The noise patches consisted of grids of 7 by 6 hand-drawn black dots, each dot 1-1.5 mm in diameter. The overall dimensions of the patches was about 1.2 by 1 cm. The noisy and noise-free positions lay on two overlapping horizontally flattened ellipses. The fixation point appeared at the midpoint of the vertical distance between the centers of these ellipses and thus provided no clue as to whether the display that followed would be noisy or not. For half the subjects, the upper ellipse was occupied by noise; for the other half, it was the lower ellipse. The dimensions of each ellipse were 6.9 cm by 3.7 cm, (6.6° by 3.5°, based on a typical viewing distance of 60 cm). The center of each ellipse was displaced by 0.95 cm above or below the fixation point. Displays of two or four items occupied one or two random axes of the ellipse, respectively. In this manner, mean distance from fixation was held constant for different display sizes, and visual quality was unpredictable to the subject and not confounded with density or distance from fixation.

Procedure. Displays remained on the screen for 150 ms. Otherwise, the procedure followed Experiment 3.

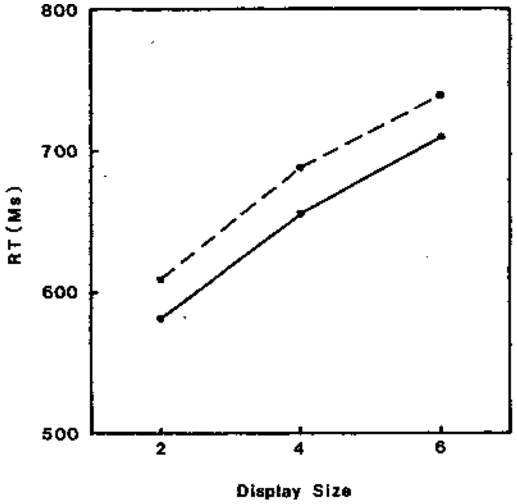

Figure 5. Mean reaction times (RTs) in milliseconds (ms) as a function of display size in Experiment 5—highest digit task. (Solid lines = noise-free display; broken lines = display with noise.)

Results

RTs less than 150 ms or greater than 1,500 ms were discarded. The data from 1 subject were discarded because of an overall error rate in excess of 20%. The average correct RTs in the six conditions are shown in Figure 5. The degradation effects averaged 26 ms, 33 ms, and 31 ms, for display sizes of two, four, and six items, respectively. The effect of quality was significant, $F(1, 11) = 76.7, p < .0001$, as was the effect of display size, $F(2, 22) = 125.7, p < .0001$. The interaction was nonsignificant, $F(2, 22) < 1$.

Error rates for high-quality displays were 0.67%, 3.75%, and 8.67% for display sizes of two, four, and six, respectively. Low-quality displays yielded error rates of 1.33%, 6.17%, and 13.58% for display sizes of two, four, and six, respectively. The effect of display size was significant, $F(2, 22) = 32.6, p < .0001$, while the effect of quality was not, $F(1, 11) = 4.6, .05 < p < .10$. The interaction was marginally significant, $F(2, 22) = 4.3, p < .05$.

The RTs and error rates by identity of the highest digit (collapsed across display sizes) are shown in Table 5. The data show the overall trend toward faster responses, with higher highest digits found in the other experiments. There is a trend toward reduced quality effects as the digit increases, as found

Table 5
RTs and Error Rates (ER) by Highest Digit and Visual Noise Condition: Experiment 5

Highest digit	Noise condition			
	Without		With	
	RT	ER (%)	RT	ER (%)
3	680	4.9	715	10.9
4	671	5.2	692	8.2
5	635	3.3	680	7.4
6	640	4.7	655	4.7
7	607	3.7	629	4.6

in the earlier experiments (when highest digit 6 was omitted). The highest digit 6 did not show the clear-cut elevation in RTs and errors observed in the previous two experiments; however, the quality effect for highest digit 5 seems anomalous. This discrepancy between this and the previous two experiments seems likely to be due to the color of display and background. Thus, the interaction of highest digit with quality reached significance, $F(4, 44) = 3.3$, $p < .05$, as did the main effects of quality, $F(1,11) = 74.8$, $p < .0001$, and digit, $F(4, 44) = 18.3$, $p < .0001$.

Discussion: Experiments 3-5

Two aspects of the results seem to be of theoretical importance. First of all, subjects' performance on the highest digit task is quite similar to that in the search tasks used in Experiments 1 and 2. This similarity is notable given the demands that the present task places on the subject in terms of (a) information that needs to be extracted from the display and (b) comparison operations that must be performed upon this information. The similar ease of performance in the two tasks seems striking to us.

This similarity is made apparent by comparing the slopes observed in the highest digit tasks (Experiments 3-5) and the search tasks (Experiments 1 and 2). For target-absent trials (i.e., those requiring exhaustive processing), the slopes were 24 ms and 27 ms per item, in Experiments 1 and 2, respectively. For the three highest-digit experiments, the slopes were 20 ms, 37 ms, and 32 ms per item. Obviously, various differences (e.g., size and nature of stimulus sets) make more precise comparisons uninformative. What is important is that the performance in a task requiring full identification of the display falls squarely within the range generally encountered when subjects are required to search for a particular prespecified character.

Our data do not conclusively rule out the possibility that search performance is achieved with stimulus analysis weaker than that required to extract identities. They do, however, argue that character identification *can* be accomplished at rates similar to those found in search tasks. This conclusion is opposite to that reached by Eriksen and Collins (1969); one might suspect that the gap-detection task they used to insure full identification (described earlier) imposed additional demands on the subject. The data also address the similar concerns raised by Rabbitt (1978), Hoffman (1978, 1979), and others about the implications of performance in search tasks.

The second noteworthy aspect of the data concerns the additive effects of display size and quality in the highest digit task. This was observed with manipulations of both intensity (Experiments 3 and 4) and visual noise (Experiment 5). As pointed out earlier, any model in which the stages of processing retarded by these quality factors are executed serially makes the clear prediction of a multiplicative interaction of these two factors. Such an interaction is not apparent in the data. In the General Discussion, various issues related to the interpretation of the quality effects in Experiments 1 -5 will be discussed.

The effects of the identity of the highest digit on RTs, and the interaction of this factor with the visual quality, will be discussed in the general Discussion as will the pattern of error data.

General Discussion

We have discussed the overall performance in the highest digit task; we now consider the joint effects of the experimental manipulations. In five experiments, additivity of visual quality manipulations with display size was observed, first in a "standard" visual search task, then in a novel task requiring subjects to name the highest digit in an array and thus presumably to access identity codes corresponding to each item in the display. This pattern of results can be taken to argue against certain serial scanning models of the character recognition process. Specifically, any model in which the stage(s) retarded by quality reduction are executed in series seems to be rejected.

Two aspects of the data suggest that the quality effects may be retarding the character recognition process itself, rather than just an early feature-extraction stage. First of all, the quality effect was larger for target-absent than target-present trials in Experiments 1 and 2 (also reported by Johnsen & Briggs, 1973). It is difficult to explain why early feature-extraction processes should be more affected by contrast when a target was not present in the display. A more natural account seems to be one in which quality affected the rate at which evidence accumulates for each character identity. If the subject had different criteria for *yes* and *no* responses, such an interaction would be expected. A variety of other research has suggested a similar conception. Becker and Killion (1977) observed that intensity interacted with semantic priming in a lexical decision task. Miller (1979) observed interactions of contrast and noise degradation with stimulus probability in choice-reaction time paradigms and concluded that stimulus quality effects retarded character identification. Both of these effects seem to lend themselves to a criterion account like that suggested above.

The interaction of quality with the identity of the highest digit, which appeared as a trend in Experiment 3 and was significant in Experiments 4 and 5, seems to have similar implications. Specifically, RTs were faster, and quality effects smaller, the higher the highest digit. Again, quality effects restricted to feature-extraction process would not be expected to behave differently according to the numerical composition of the display. It is interesting to consider what might cause this pattern of results, a question that requires considering how subjects may be performing this seemingly complex task.

The problem of finding the highest digit in an array would commonly be implemented on a digital computer with something like the following algorithm: (1) Let current-highest digit = 0; (2) get the next item; (3) if it is higher than the current highest, assign its value to current highest; (4) return to Step 2. Plainly, the time required would be basically proportional to the length of the list. If subjects are using such an algorithm in Experiment 3, for instance, then the sum of the execution times of Steps 2, 3, and 4 must be on the order of 20 ms, and this estimate assumes that the display size slope originates exclusively in this comparison process. Although present knowledge is not decisive on whether processes of this sort could be carried out at such a rate in human neural architecture, we suggest that this seems unlikely (see Anderson, 1977).

Instead, we suggest that the decision stage may itself be executed without serial comparisons. There are a variety of ways this might be done. To use a spatial metaphor, the stimuli might activate (in parallel) internal representations arrayed as nodes along the number line, and a central mechanism might simply select the "rightmost" node without need to engage in pairwise comparisons. Obviously, various nonspatial models could instantiate basically the same idea. According to this view, the central processes might have available to them a continuous indication of the highest item among the digits currently available.

Such an idea may suggest a partial explanation for two aspects of the present data: faster RTs and smaller quality effects with higher highest-digits. If central processes have continuous access to the current highest digit, given current stimulus evidence, then they must decide when to move on to response selection (presuming a discrete boundary between these stages; see Miller, 1982, 1983). Suppose the criterion of when to select a response is related to the amount of evidence accumulated in the recognition process. On various assumptions, it would be optimal for the decision process to insist upon more assurance about the identities, the lower the apparent highest item. This is due to the statistical fact that if identification errors have occurred due to insufficient information, the probability that an omitted item is in fact higher than the apparent highest is greater, the larger the number of higher digits in the total stimulus set (note that confusion errors would have a more complex pattern of effects). Therefore, given a strategy of jointly minimizing time and errors, it would appear rational to base the decision to respond on a trade-off between how large the current highest is and how much evidence has accrued at the stimulus recognition level. Thus, the highest-digit identity effect may operate similarly to the target presence/absence effect, and interact with visual quality for similar reasons.

The main effects of display size have not been specifically addressed yet. Evidently, they do not result from criterion adjustments of the sort suggested to account for target presence/absence effects, or else interactions of display size and visual quality would be expected. The display size slopes may result from various limitations at a number of different stages, although certain capacity limitation models seem to be ruled out by the lack of interaction between display size and visual quality. Some of the display size effects may originate in postencoding decision or response-selection processes. Another possible factor is that deployment of visual attention may be necessary before encoding can begin (a point discussed in more detail below); this deployment may occur more slowly for larger displays (cf. related suggestions of Harris, Shaw, & Bates, 1979). Finally, other possible contributing factors include variability in encoding rates (relevant to target-absent trials; see Footnote 1), and lateral inhibitory effects.

There is an alternative account of the behavior of stimulus quality in these experiments that would yield the interactions observed while maintaining that quality affects the rate of feature extraction. This account hypothesizes an optional checking procedure in which subjects reexamine one or more display elements on certain trials. It is necessary to assume that the probability of checking is related to quality, target presence-absence, and magnitude of highest digit. We cannot definitively reject this account, but it has consequences that may be judged implausible. For instance, the probability of re-checking would have to be independent of display size, and its duration would have to be essentially unaffected by display size. Systematic examination of RT distributions with large data sets might make it possible to test certain accounts of this sort.

Another aspect of the data requiring comment involves the interactions of display size with visual quality observed in the error rates in Experiments 1, 3, and 5 (the experiments with brief displays). These interactions might be taken to undermine our arguments by providing an indication of a speed-accuracy trade-off, which is obscuring the fact that the stages retarded by quality variables are actually executed serially in our tasks. Suppose that the effect of quality in Experiment 1 *is* to slow down sequential encoding processes. Because the quality effect for two items is approximately 50 ms (target absent), we might assume that the quality effect for six items would be 150 ms if the process were to operate with the same criteria. To obtain additivity, then, it would be necessary to readjust criteria to accomplish a saving of 100 ms. Such a compression might operate either on the encoding process itself or on later stages (Taylor, 1976) or on both. First of all, it seems implausible that such a large compression could be accomplished without a very gross impairment in accuracy. Further, the amount of compression would have to be even more extreme to account for the results of Johnsen and Briggs' (1973) experiment, which involved much larger quality effects and display size ratios of four to one.

But there is a much more severe problem one faces in developing any such strategic account. In addition to invoking enormous compensatory adjustments, one also needs to account for *why* the quality and display size effects should end up additive. For present purposes one would have to postulate that the decision criterion is adjusted to provide a constant effect of the quality manipulation across varying display sizes. This amounts to explaining an additive effect by suggesting that the system is strategically adjusted for the express purpose of producing the additive effect. Essentially, it says that strategies are employed specifically to eliminate interactions, but not to eliminate main effects! In addition, such an account would have to explain the overadditive interactions of quality with target presence/absence in Experiments 1, 2, and Johnsen and Briggs (1973) and with highest digit identity in Experiment 4. It is not clear how criterial adjustments would operate to preserve these particular interactions while eliminating others. In short, strategic accounts of the additivity of quality and display size, which maintain that the stage(s) affected by quality are executed serially, seem highly improbable.

Thus, the interactions in error rates do not undermine the arguments against serial encoding. Distinct from that question, however, is the possibility that they indicate capacity limitations (still consistent with parallel encoding). We do not believe that the present data are decisive either way as to the question of whether processing multiple items simultaneously produces a reduction in the quality of information extracted. In general, we suggest that different experimental approaches are most decisive on these related but different kinds of attentional questions. The sort of chronometric analysis used here seems best suited to addressing the parallel/serial question (subject to possible uncertainties about the locus of visual quality effects). Examination of accuracy in data-limited situations (e.g., Kinchla, 1977; Shaw, 1980) seems suited to detecting capacity limitations but provides little information relevant to the parallel versus serial question or to the locus of any information loss that may be inferred. A unified theory will ultimately need to address both issues and possible processing differences between speeded and data-limited tasks.

Theoretical Issues

The conclusions about parallel multielement processing that were suggested above are congenial to strong late-selection theories of attention (e.g., Duncan, 1980b; Shiffrin, 1976). However, such theories go well beyond the conclusions warranted by the present work and other converging findings (Shiffrin & Gardner, 1972), and, we believe, they are called into question by various recent studies.

The essential element of late-selection theories is the claim that recognition of well-learned patterns is not only unlimited in capacity but also entirely unselective in its application. The system is said to preattentively compute representations at all levels for all stimulus patterns delivered by the sensory receptors. If pattern recognition is unselective, plainly there must be other mechanisms for selection by attributes like color and location. Duncan (1981) pointed out the role of late-selection mechanisms in various paradigms, positing the assumption that they operate on already computed ("post-categorical") representations. It is clear, however, that the possibility of parallel identification of multiple items, suggested by present results and others, by no means entails that such analysis always occurs unselectively.

The arguments for completely unselective processing have always hinged on demonstrations of indirect effects from unattended stimuli, for example, Stroop-like effects (Eriksen & Hoffman, 1973; Stroop, 1935). More recent results have suggested that these effects can be greatly reduced by manipulations that might be expected to make filtering easier (Francolini & Egeth, 1980; Kahneman & Treisman, 1984). An especially compelling case for filtering seems to be suggested by some interesting results of Duncan (1979). Duncan required subjects to search for a target in just a subset of the positions on a circle occupied with characters, that is, the subject was to ignore target presence or absence in the irrelevant positions. When the relevant distractor positions were filled with items capable of recombining to form the target (as in Experiment 2 above), the slopes relating RTs to number of relevant positions were substantially increased. On the other hand, whether or not the *irrelevant* positions were composed of such elements made no significant difference. Duncan interprets this as meaning that the effect of potential recombination is postattentive; such a claim is difficult to square with any notion that attention accesses fully identified representations. This claim seems to entail the assumption that the effect of potential illusory conjunction of distractors occurs *after* letter identification. It is hard to imagine what such an effect might be. On the other hand, Duncan's finding fits well with a rather older idea: that filtering actually prevents items from undergoing certain kinds of analysis (Broadbent, 1958).

Another result that seems to conflict rather directly with the basic tenets of late selection was reported by Pashler (1984). Subjects classified a spatially probed single element from a display of eight characters. When the entire display was previewed for 300 ms, there was no significant reduction in the effect of target discriminability or contrast. If the late-selection account were correct and if the spatial selection triggered retrieval *of a fully encoded* item, one would expect virtual disappearance of these RT effects. Comparison with the present results may point toward an interesting paradox. Apparently, subjects can extract identities from an entire display simultaneously (Experiments 1-5 above); however, if they have the opportunity to preview a display, and then a spatial probe appears, they must still proceed to encode the probed item.

It should be noted, however, that there are possible accounts of Pashler's (1984) findings not completely at odds with late-selection theories. First of all, the encoded visual information might rapidly decay even when the display remains available. Second, it is possible that subjects for some reason optionally fail to make use of the encoded representation, even though they have obtained it. Third, it is possible that the results do not really indicate that the subject was encoding the target item after probe presentation in the preview condition; conceivably, the stimulus factors had unexpectedly large effects on decision processes or even on the time to shift attention to the item once the probe appeared. A more interesting possibility, mentioned in the earlier article, is that the need for accurate *selection by location* in the bar-probe paradigm played a crucial role.

A full resolution of these issues will require more extensive research. We suggest the following speculations. Suppose parallel encoding processes are capable of extracting the identities present in a multielement display but not of tying those identities to locations in a centrally accessible format. That is, long-term memory codes are activated, but a spatial map including those identities is not created. In that case, tasks like the highest digit task (Experiments 3-5 above) could utilize the products of simultaneous encoding. On the other hand, the information extract-able during a display preview would be of no value for later spatial selection (Pashler, 1984); selective encoding by location would be necessary.

If parallel pattern recognition does not produce a representation that includes centrally accessible spatial information, then subjects will have no way to perform spatial selection unless they can suppress the encoding of irrelevant locations. Thus, this account requires that genuine filtering by location exist, but it differs from classical filtering views (Broadbent, 1958) in suggesting that the "filter" may optionally be set to encompass multiple objects, resulting in parallel identification of these stimuli. Thus conceived, the parallel analysis would not be preattentive and automatic; rather, it would depend upon a controlled (wide) distribution of visual attention. Filtering tasks (like the bar-probe task) would be performed with a narrow deployment of visual attention. This narrow deployment may be the *only* mechanism for spatial selection, that is, there may be no *additional* mechanisms for spatial selection operating upon postcategorical representations (Duncan, 1981).

Although there may not be a centrally accessible maplike representation of identities and locations, subjects' impressive ability to locate detected targets (Sperling, Budiansky, Spivak, & Johnson, 1971; Treisman & Gelade, 1980) still needs to be accounted for. At some level, it seems, parallel analysis of identities (resulting from a wide deployment of spatial attention) must maintain corresponding locational information. We suggest that the correspondence might be in a form *enabling* a shift of visual attention rather than providing a declarative maplike representation available for central inspection. Target location might be obtained simply because detection initiates a (possibly automatic) shift of spatial attention. It follows that target detection should selectively reduce concurrent discrimination for target-distant stimuli; interesting evidence for this was reported by Hoffman, Nelson, & Houck (1983). Of course, in suggesting the need for filtering, we are not suggesting that any items can be completely excluded (Eriksen & Hoffman, 1972).

At a more general level, this conception entails that *selection* can occur at various levels of processing, depending on the demands of the task. If the task requires only selection by identity information (as in the highest digit task reported above), then a wide deployment of visual attention will allow parallel extraction of all identities in the display. The subsequent selection is cognitive, not attentional, though it may initiate an automatic attentional shift. If the task requires selection by (prespecified) spatial location(s), then it is performed by focusing attention on the location(s), restricting encoding to the item(s) appearing there. Because visual attention is specifically spatial, other kinds of apparent filtering may in fact operate indirectly. For instance, if the task requires selection by color, the entire display would be analyzed in parallel to extract the color of all items. An attentional shift would then be executed to focus attention on the spatial site(s) of the target color; the item's identity can then be extracted to the exclusion of other items in the display. Note that errors in the shift might be expected to result in the report of neighboring items; such an effect was observed by Snyder (1972). Thus, subjects may "filter by color" by shifting spatial attention to target-color *positions,* much as they locate target characters.

It would be premature to develop such an account any further. The present results have provided converging evidence for the idea of parallel encoding and have provided evidence to bolster the idea that this simultaneous analysis can take the form of object identification rather than just feature extraction (Treisman & Gelade, 1980) or target/background discrimination (Eriksen & Collins, 1969; Hoffman, 1978, 1979; Rabbitt, 1978). More generally, a number of results in the literature reviewed here do not seem to fall clearly in line with either the traditional early- or late-selection frameworks. Careful distinctions among different kinds of information extraction, as well as further empirical work, will surely be needed so that the basic limits on visual information processing can be better understood.

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