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The Preattentive Emperor Has No Clothes: A Dynamic Redressing

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Preattentive models of early vision have not been supported by the evidence. Instead, an input filtering system, which is dynamically reconfigured so as to optimize performance on the task at hand, is proposed. As a case in point, the authors examined Sagi and Julesz's (1985a) claim that detection tasks are processed preattentively and efficiently (shallow search slopes), whereas discrimination tasks require focal attention and yield inefficient steep slopes. In 5 visual search experiments, efficiency was found to depend not on the nature of the task but on whether the task is single or dual. The second component of a dual task, whether detection or discrimination, is performed inefficiently if it does not fit the configuration of the input system, which had been set optimally for the first component. But, even the second component is processed efficiently if there is enough time to reconfigure the system after processing the first component.

Searching for a hidden target among distractors is said to involve two broadly sequential processing stages (Julesz, 1984; Neisser, 1967; Treisman & Gelade, 1980). In the first, *preattentive* stage, processing is said to be performed rapidly and in parallel across the entire visual field. In the second, *attentive* stage, processing is said to be serial, of limited capacity, and aimed principally at binding different features into objects within a restricted portion of the visual field.

A central tenet of this bipartite scheme is that, on entering the visual system, the image is decomposed into elementary features, which are then reassembled at later processing stages. The initial decomposition is thought to be performed by built-in analyzers that respond automatically to specific stimulus attributes such as spatial frequency, orientation, color, and motion. These analyzers are said to function in parallel, without any need for attention, and to be replicated throughout the visual field, so as to be readily accessible to stimuli presented in any spatial location. The information encoded at this preattentive stage is then made available to a later, attentive stage where it is assembled into meaningful objects.

Studies of visual search have distinguished between these two processing stages by means of the slope of the function relating a measure of performance, such as search time or accuracy, to the number of distractors in the display. A flat or shallow search slope indicates that the time to find the target is unaffected by the number of distractors. This has been regarded as consistent with the operation of parallel, unlimited-capacity, preattentive analyzers in the first processing stage. A steep slope, on the other hand, indicates that the time to find the target increases with the number of distractors. This points to a sequential search through the items in the display and has been regarded as consistent with the operation of the serial, capacity-limited attentive mechanisms of the second stage (Neisser, 1967; Sternberg, 1966; but see Egeth, 1966, and Townsend, 1990, for a diverging viewpoint).

Although it accounted successfully for the early results, this dualistic viewpoint has been seriously questioned by more recent evidence. For example, one might expect that the search slopes reported in the literature should be distributed bimodally, revealing two underlying distributions: one composed of flat or shallow slopes obtained with displays amenable to parallel preattentive processing and the other composed of steeper slopes obtained with displays that required serial search. In fact, the results of over one million visual-search trials, involving many different tasks, revealed a single, unimodal distribution of slopes, thus, disconfirming expectation based on a dualistic scheme (Wolfe, 1998).

A systematic case against the dualistic scheme has been presented by Nakayama and Joseph (1998), who questioned the notion of a low-level preattentive stage on several grounds. From a practical standpoint, the list of features capable of supporting parallel search seems to have grown beyond biological plausibility. Besides simple primitive features, the list now includes such complex stimuli as letters of various fonts and sizes, 3-D cues, and

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shading effects (e.g., Enns & Rensink, 1990, 1991; He & Nakayama, 1992; Kleffner & Ramachandran, 1992; Ramachandran, 1988; Wang, Cavanagh, & Green, 1994). This proliferation of preattentive features led Nakayama and Joseph to comment pointedly as follows:

> Although dense feature maps may exist for simple features such as color and orientation, it becomes much more difficult to conceive of an exhaustive set of maps for various letters, surface shapes, and so forth. Moreover, with the report of each new example of an element supporting rapid visual search, yet another map of primitives is needed, also represented densely at different retinotopic locations and scales. (Nakayama & Joseph, 1998, p. 282)

Adding to the weight of contrary evidence, recent studies have questioned the very phenomena that the dualistic model purported to explain. It has been shown that even those tasks that involve only primitive features such as line-orientation or random-dot motion can yield steep search slopes when attention is severely divided (Joseph, Chun, & Nakayama, 1997; Kawahara, Di Lollo, & Enns, 1999). Thus, the steepness of the slope depends not on whether the search can be done at the level of early built-in analyzers, but on whether sufficient attentional resources are available, given the viewing conditions. This implies that not even the simplest, most primitive features can be processed without attention. These, and related findings reviewed by Nakayama and Joseph (1998), bring into question the necessity, or even the usefulness, of postulating an encapsulated preattentive stage that performs early visual operations in an all-or-nothing fashion.

A Dynamic Alternative

A notable drawback of a hard-wired preattentive module is its inflexibility. As an alternative, we explore the option of a more versatile early stage, capable of supporting efficient search, yet not relying on rigidly built-in units to achieve efficiency. One such option was proposed by Visser, Bischof, and Di Lollo (1999) for explaining the effects of attentional switching in a wide range of experiments. In that model, the initial processing is performed by a set of input filters whose functional characteristics are programmable under the control of prefrontal cortex. Instead of the built-in analyzers postulated in the dualistic scheme, this model relies on versatile mechanisms that are dynamically reconfigured so as to handle incoming stimuli with maximum efficiency.

Reconfiguration is part of a comprehensive, goal-directed process aimed at tuning the visual system to those attributes and characteristics of incoming stimuli that are likely to prove useful for performing the task at hand. The process of reconfiguration is likely to involve most levels of the visual system and to be under the control of prefrontal cortex. Monsell (1996) has referred to this process as *task-set reconfiguration*. In Monsell's (1996) view, this is ". . . a process of enabling and disabling connections between processing modules and/or re-tuning the input-output mappings performed by these processes, so that the same type of input can be processed in the different way required by the new task" (p. 135). A similar concept was held by William James (1890/1950), who termed it *ideational preparation* or *adaptation of attention*. This can be conceived symbolically as

> . . . a brain-cell played upon from two directions. Whilst the object excites it from without, other brain-cells, or perhaps spiritual forces, arouse it from within. The latter influence is the 'adaptation of the attention'. *The plenary energy of the brain-cell demands the co-operation of both factors:* not when merely present, but when both present and attended to, is the object fully perceived. (p. 441; italics in the original)

Stimuli that fit the characteristics of the input filter are handled efficiently, yielding shallow or flat search slopes, possibly indicative of parallel processing. Other stimuli are handled less efficiently and yield correspondingly steeper search slopes, suggestive of serial processing. Dynamic input filtering of this kind can equal the processing efficiency of a hard-wired preattentive module, but it avoids the biological implausibility, not to mention the lack of parsimony, of proliferating built-in analyzers. This is because a limited set of basic components can be dynamically reconfigured to perform a range of different functions efficiently, as required.

A limitation of this type of system is that efficient processing is restricted to those stimuli whose attributes and characteristics fit the current configuration of the input filters. This can lead to situations in which even the simplest and most primitive stimulus may be processed inefficiently if it does not fit the current configuration. A study by Joseph et al. (1997) provides an apposite example. The stimulus was a set of uniformly oriented Gabor patches flashed briefly on the screen, followed by a masking pattern. Observers detected the presence or absence of an oddball patch of the opposite orientation. Performance was highly efficient, as indicated by a flat search function. However, the very same oddball task was performed inefficiently when it was done second in a dual-task sequence. In that sequence, the oddball task was preceded immediately by a letter-identification task, which was performed efficiently. From the standpoint of dynamic input filtering, the oddball task was performed efficiently when it was done in isolation because the system was configured so as to optimize detection of an oddball orientation. In the dual task, however, the system was initially configured to optimize letter identification, which was performed efficiently, but could not be reconfigured for oddball detection in the time available. Oddball detection improved when the two tasks were separated by longer time intervals, during which the system could be reconfigured in readiness for the second task. Needless to say, the finding that the processing of such a primitive feature as orientation is affected by the distribution of attention is entirely inconsistent with a built-in preattentive stage.

Far from being an isolated example, the findings of Joseph et al. (1997) are representative of a class of events, often referred to as *attentional switching* or *task switching*, which reveal the functioning of the dynamic input system advocated here. At a more general level, we believe that the distinction between preattentive and attentive processing, drawn in earlier studies, depends not on whether the stimuli match the characteristics of early built-in analyzers but on whether a rapid task switch prevents the system from being suitably reconfigured. We pursue this line of reasoning in the present work with particular reference to the classical study of Sagi and Julesz (1985b), which is widely regarded as epitomizing the distinction between preattentive and attentive processing stages. In a series of five experiments, we show how the steep search slopes reported in the study of Sagi and Julesz (1985b) and in other similar studies, came about not because the task could not be done preattentively but because an attentional switch was inherent in the task that was said to require serial attentive scrutiny.

The Work of Sagi and Julesz

In the following description of the work of Sagi and Julesz (1985a, 1985b), and in the remainder of this article, the terms *detection* and *discrimination* are used strictly as defined by Sagi and Julesz (1985b), despite some ambiguity. As noted below, Sagi and Julesz's "detection" task might be described more aptly as a subitizing task, and their "discrimination" task as a combination of two oddball detection tasks. Ambiguities such as these often arise when vernacular terms are used to denote experimental effects. Nevertheless, to maintain consistency of terminology, we chose to adopt both of those terms as operationally defined by Sagi and Julesz (1985b).

In the studies of Sagi and Julesz (1985a, 1985b), the display consisted of a field of line segments, all of which had the same diagonal orientation, except for a few target lines, which could be either vertical or horizontal. On half of the trials, all lines in the target set were oriented uniformly, either vertically or horizontally. On the remaining trials, one target line had the opposite orientation to the other target lines. Observers performed two tasks. In the *detection* task, they simply reported the number of lines in the target set, regardless of orientation. Performance in this type of task is said to be governed by local differences, or gradient discontinuities, between the target lines and the surrounding background lines. Such "feature-gradient" tasks typically yield flat search functions and, therefore, are said to be performed in parallel and not to require attentional resources (Sagi & Julesz, 1985b). In the *discrimination* task, observers reported the presence or absence of an oddly oriented line within the target set. According to Sagi and Julesz (1985b), the distinguishing characteristic of this task is that it involves identification of the target's orientation, a process that is performed serially and requires attentional resources: "... identification of even a single feature such as orientation requires some time-consuming processing by focal attention" (p. 1218).

Processing load was manipulated in both tasks by varying the number of items in the target set. It was found that as the number of target lines was increased, performance was correspondingly impaired in the discrimination task but not in the detection task. That is, discrimination search slopes were steep, whereas detection slopes were flat. From this it was concluded that attentional resources are required for processes that involve identification, but not for processes that involve only detection.

An Alternative Account

On the face of it, this was a plausible inference, based on the slopes of the search functions obtained in the two tasks. Closer scrutiny of the stimuli and tasks, however, brings that conclusion into question. Specifically, it is not clear whether a process of identification was necessarily involved in the discrimination task. Consider the implicit sequence of events in performing that task. The main objective was to detect an oddball line in the target set. To do that, however, it was first necessary to segregate the lines in the target set from the background lines. This suggests that the discrimination task may involve two implicit steps. The first is a texture-segmentation process by which the lines in the target set are segregated from the background lines. This is a feature-gradient task, akin to the detection task, in which the target lines are held to "pop out" preattentively through local differences, or gradient discontinuities, formed against the background texture of diagonal lines. The second is also an oddball detection process by which the presence or absence of an oddly oriented line within the target set can be determined without having to identify its actual orientation. The important consideration is that both steps consist of detection processes that can be performed without identifying the actual orientation of the lines in the target set.

On this reasoning, the different search slopes obtained in the detection and discrimination tasks cannot be attributed unambiguously to different underlying processes (i.e., detection vs. identification) because both tasks may involve only detection of oddball orientations or gradient discontinuities. Instead, a critical determining factor may have been the number of implicit steps necessary to complete each task. Although detection involved the single task of subitizing the discontinuities in the orientation gradient, two sequential steps may have been required in the discrimination task: The first was to segregate the target lines from the background, and the second was to detect the oddball line within the set of target lines. Thus, in Sagi and Julesz's (1985b) discrimination condition, observers may have been faced with an implicit dual task, which involved an attentional switch between the first and second component.

We are led by this line of reasoning to the following suggestion. The steep discrimination slopes in Sagi and Julesz's (1985b) study might have arisen not because the task involved identification but because it involved an implicit attentional switch. From the standpoint of dynamic input filtering, one might say that the system was initially configured to do a texture-segregation task, which it performed efficiently, but could not be reconfigured in time for the oddball task, which it performed inefficiently. We examined this hypothesis by using the same stimuli as in Sagi and Julesz's (1985b) detection task. However, the detection was done either as a single task, as in Sagi and Julesz's study, or as part of a dual task. The resulting search slopes were flat in the single task, but steep in the dual task, even though both tasks involved only detection.

Experiment 1

Detection in Single and Dual Tasks

Experiment 1 had two conditions. The first was a *single-task* condition identical to Sagi and Julesz's (1985b) detection task, in which observers reported the number of horizontal or vertical target lines amongst diagonal background lines (see Figure 1a). The second was a *dual-task* condition designed to test the attentional-switching hypothesis. The displays in this condition were the same as in the single task, except that a hexagonal frame surrounded the stimulus array. As illustrated in Figure 1b, the top and bottom lines of the hexagon were always tilted away from the horizontal. Observers made two responses in this condition. First, they indicated whether the top and bottom lines of the hexagon had the same orientation. This was designated as the primary task, to which observers were instructed to pay full attention. Second, they reported the number of target lines in the array, as in the single-task condition. Thus, both conditions had identical detection re-

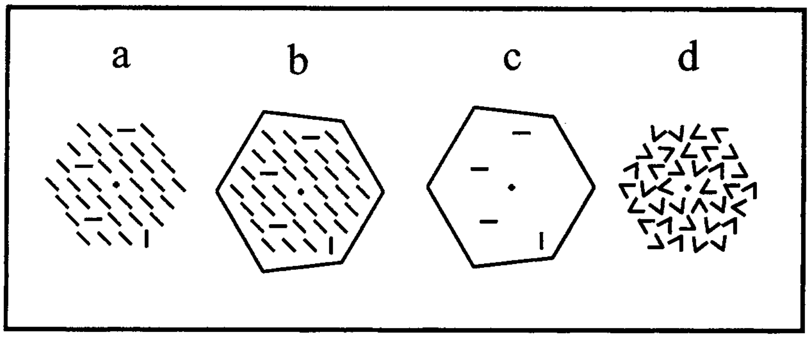

Figure 1. Schematic representation of the stimuli used throughout the present experiments.

quirements. However, in the dual-task condition, the detection was preceded by an unrelated task. On the hypothesis of dynamic input filtering, we expected steeper search slopes in the dual-task condition because the input system was initially configured optimally for the outline task and, as a consequence, could not handle the oddball task efficiently.

Method

Observers. Three authors and 1 undergraduate student, who was unaware of the purpose of the experiment, participated in the study. All had corrected-to-normal vision and performed approximately 2,000 practice trials before beginning the experiment.

Apparatus and stimuli. Stimuli were displayed on a Tektronix 608 oscilloscope equipped with P15 phosphor. Observers viewed the displays in a dark room, except for dim illumination of the keyboard. The viewing distance was 57 cm, set by a headrest. The stimulus array consisted of 36 line segments, each subtending 0.8° of visual angle, with thickness less than 0.1°. The line segments were arranged in the hexagonal pattern illustrated in Figure 1a. The diameter of the hexagon was 6.5°. All line segments had the same diagonal orientation (either 45° clockwise or anticlockwise, determined randomly on each trial), except for a few target lines, which were vertical or horizontal. On half the trials, all target lines were oriented in the same direction, either vertically or horizontally. On the remaining trials, one target line was oriented in the opposite direction. The target lines were positioned randomly within the stimulus array, with the constraint that they be separated by at least two diagonal lines. In the dual-task condition, a hexagonal frame surrounded the stimulus array. Its diameter was 7.5° with thickness less than 0.1°. As illustrated in Figure 1b, the top and bottom lines of the hexagon were always tilted 14° away from the horizontal, clockwise or anticlockwise. This resulted in two types of hexagons: parallel or diverging. In both the single- and the dual-task conditions, the stimulus display was followed by a masking pattern, consisting of 36 randomly rotated Vs, as illustrated in Figure 1d.

Procedure. Each trial began with a small fixation cross, which remained in the center of the screen throughout the display sequence. Observers initiated each trial by pressing the space bar. After a 500-ms delay, the relevant stimulus display was presented for 5 ms. The masking pattern was then presented for 10 ms at an interstimulus interval (ISI) the duration of which was under the control of the PEST staircase procedure described below. Because the displays were very brief, the luminance was set at a relatively high level to compensate for the time-intensity reciprocity known as Bloch's law. The luminance of the stimulus array was set at 400 cd/m^2, and that of the mask pattern at 300 cd/m^2, as measured by a Minolta LS-100 luminance meter. This made the displays comfortably visible.

In the single-task condition, observers reported the number of target lines, irrespective of their orientation. In a given block of trials, the number of target lines was fixed at (a) 1 or 2, (b) 2 or 3, or (c) 3 or 4, as in the detection condition of Sagi and Julesz (1985b). Because there were only two response alternatives in any given block of trials, observers pressed the left arrow key to indicate the lesser number of targets and the right arrow key to indicate the greater number of targets. Within a block of trials, the lesser and greater numbers of target lines were presented randomly and with equal probability. A dynamic threshold-tracking procedure (PEST, Taylor & Creelman, 1967) was used to converge on the critical target-mask ISI at which the observer made approximately 85% correct responses. Four such estimates were obtained in each combination of condition and number of target lines. Each point in Figure 2 represents the average of the four estimates.

In the dual-task condition, two responses were required. First, observers pressed either the *Z* or the *X* key on the keyboard to indicate whether or not the top and bottom lines of the hexagon were tilted in the same direction. Second, observers reported the number of target lines regardless of orientation, by pressing the left or the right arrow key, as in the single-task condition. The comparison of the top and bottom lines of the hexagon was the primary task, to which observers were instructed to pay full attention. The fact that performance on this task was consistently above 90% correct indicates that observers complied with this instruction. The PEST procedure tracked performance in the secondary task, in which observers reported on the number of lines in the target set. In converging toward the

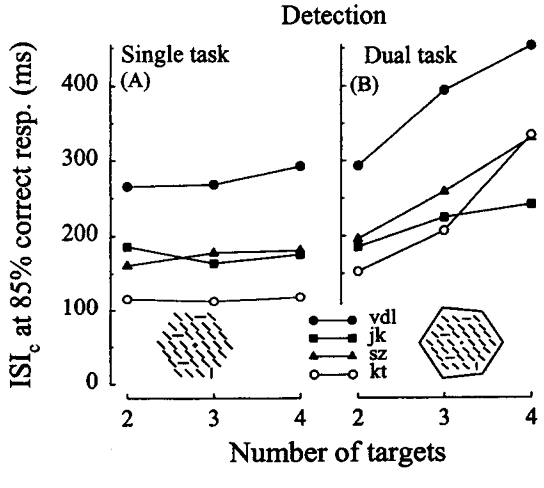

Figure 2. Mean critical interstimulus interval (ISI$_c$) in Experiment 1. The insets illustrate the display patterns used in the single-task (A) and in the dual-task (B) conditions. resp. = response.

critical ISI, PEST utilized only those trials on which the response to the primary task was correct. This was done because, on incorrect trials, attention may not have been focused on the primary task, in which case the occurrence of an attentional switch would be moot.

One experimental session contained three blocks of trials. Each block yielded one estimate of the critical ISI for one combination of condition (single or dual task) and target-set size (1 or 2, 2 or 3, 3 or 4), in a new random sequence for each session. Each observer served for a total of eight sessions.

Results and Discussion

Critical ISIs, averaged over the four replications, are shown in Figure 2 as a function of target-set size, separately for the 4 observers in the single- and dual-task conditions. The pattern of results was very similar for all four observers, whether experienced or naive. Critical ISIs remained approximately constant as a function of target-set size in the single-task condition, but increased steeply in the dual-task condition. Linear regressions through the individual points in Figure 2a yielded slopes of 6.8, −5.2, 10.2, and 1.3, for Observers VDL, JK, SZ, and KT, respectively. The corresponding slopes in the dual-task condition (Figure 2b) were 80.0, 27.9, 67.0, and 90.1. Averaged across observers, the dual-task slopes were steeper than the single-task slopes by a factor of 20.2, confirming the graphical evidence in Figure 2 that search slopes were substantially steeper in the dual-task conditions. Percentages of correct responses in the primary task, in which observers judged whether the upper and lower sides of the hexagon were parallel, were 92.7, 92.3, 96.2, and 96.8, for Observers VDL, JK, SZ, and KT, respectively.

If the slope differences in Figure 2 are to be ascribed unambiguously to the processing requirements in single versus dual tasks, then a possible source of confound must be considered and dismissed. The dual-task displays were framed by a hexagonal outline, which was not part of the single-task displays. It is possible that the mere presence of a surrounding frame might have made the task more difficult and the search slopes steeper, whether or not observers were required to attend to it. To examine this option, we replicated the single-task condition with displays framed by a hexagonal outline (as in the dual-task condition). which observers were instructed to ignore. The slopes of the search functions were −2.6, −10.7, 7.9, and 3.3 for Observers VDL, JK, SZ, and KT, respectively. These slopes are very similar to those in Figure 2a, strongly suggesting that the slope differences seen between Figures 2a and 2b were due to inherent differences between single and dual tasks, not to the presence or absence of the frame.

The difference between the search slopes in Figures 2a and 2b echoes the difference obtained by Sagi and Julesz (1985b, Figure 2) between detection and discrimination tasks. But the explanation proposed by Sagi and Julesz cannot account for both sets of results. According to Sagi and Julesz, the discrimination task yielded relatively steep search slopes because it involved a process of identification which, unlike detection, requires focal attention and serial processing. Although it accounts adequately for Sagi and Julesz's results, that explanation is inadequate for the present study because the dual-task condition, which yielded slopes comparable to those in Sagi and Julesz's discrimination condition, involved only processes of detection which are held to be carried out preattentively and in parallel. On the other hand, a common account can be given for both sets of results if it is assumed that Sagi and Julesz's discrimination task involved two sequential detections, thus turning it into an implicit dual task. We have argued in the foregoing that performance of a dual task involves a resetting of input filtering mechanisms from a configuration optimally tuned to the characteristics of the first task to one tuned to those of the second. If such a reconfiguration cannot be achieved in the time available, performance of the second task will suffer.

A detail of the results in Figure 2 invites special comment. The critical ISI obtained by any given observer in the dual-task condition when the display contained only two targets, matched that obtained by the same observer across all set sizes in the single task. This suggests that the adverse effect of an attentional switch under dual-task conditions did not become evident unless the processing demands of the secondary task exceeded a certain level. A similar result has been reported by Braun and Sagi (1990, Experiment 3) who found that detection performance in a dual task was unimpaired in comparison with detection in a single task. Notably, the secondary target in Braun and Sagi's study consisted of a single element. Failure to reveal dual-task interference with such a small target set matches the present finding and may be ascribed to the modest processing requirements of the secondary task.

One more option needs to be considered before reaching a definitive conclusion. We need to consider whether the present results and those of Sagi and Julesz (1985b), while sharing many similarities, might be independent events arising from separate causes. For example, it may be suggested that Sagi and Julesz's discrimination task might, indeed, involve identification of the orientation of the target lines, whereas no identification was required in the present dual task. In that case, Sagi and Julesz's steep discrimination functions would be caused by the task's identification requirement, whereas those seen in Figure 2b would be caused by the dual nature of the task. This option is examined in Experiment 2.

Experiment 2

Discrimination With and Without Background Texture

In Experiment 1, a simple detection task yielded either shallow or steep search functions, depending on whether it was performed as a single or as a dual task. One might say that the way in which the detection was performed could be changed from efficient (shallow search slope) to less efficient (steep search slope) by changing the task from single to dual. Experiment 2 was designed to investigate the converse case, with specific reference to the discrimination task used by Sagi and Julesz (1985b).

We have argued in the foregoing that the discrimination functions obtained by Sagi and Julesz (1985b) were steep not because the task involved identification of the lines' orientations but because it was, in practice, a dual detection task. On this view, the main function of the diagonal background lines in the display (Figure 1a) was to mediate the first step in the dual-task sequence by creating the need to segregate the target lines from the background texture. In the language of input filtering, this created the need to reconfigure the input system from one tuned optimally for texture segregation to one tuned optimally for oddball detection.

In designing the present experiment, we reasoned that, if the steep discrimination slopes obtained by Sagi and Julesz (1985b) arose from the need to reconfigure the input system, then omitting the background texture would obviate the need for the first step and, therefore, eliminate the need for reconfiguration. In practice, this would change the task from dual to single. The resulting search functions should then change from steep to shallow. On the other hand, if the discrimination task yielded steep slopes solely because it involved identification, as claimed by Sagi and Julesz (1985b), then omission of the background lines might make the task easier by reducing the level of background noise, but the slope of the discrimination function should remain largely unaffected. This is because the task would still involve identification, whether the background lines are present or absent.

These expectations were tested in Experiment 2, using Sagi and Julesz's (1985b) discrimination task. Observers indicated whether one target line had the opposite orientation to the remaining lines in the target set. There were two types of displays. In one, the target lines were displayed within a background of diagonal lines, as in the study of Sagi and Julesz (1985b, Figure 1a). In the other, the background lines were omitted. We found that the search slopes were steep when the background lines were present but shallow when they were absent, favoring a dual-task interpretation.

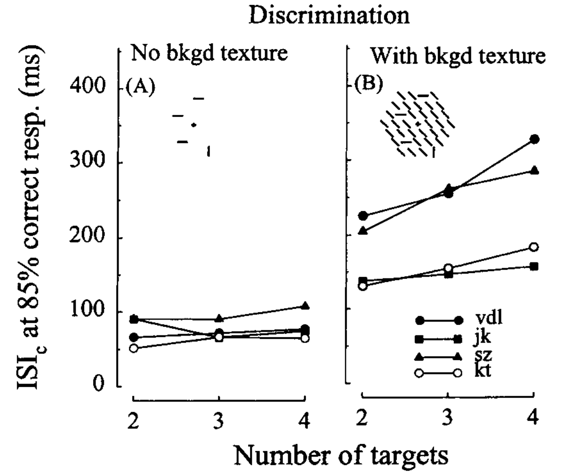

Figure 3. Mean critical interstimulus interval (ISI$_c$) in Experiment 2. The insets illustrate the display patterns used in the condition without background (bkgd) texture (A) and in the condition with background texture (B). resp. = response.

Method

Observers, apparatus, and procedures were the same as in Experiment 1, with the following exceptions. The target set contained either two, three, or four lines. On half of the trials, sequenced randomly, all target lines had the same orientation, either vertical or horizontal, with equal probability. On the other half of the trials, one line had the opposite orientation to the other target lines. Observers reported on the presence or absence of an orientation oddball in the target set by pressing the left or the right arrow key on a keyboard. The target set was displayed either within a background of diagonal lines, as illustrated in Figure 1a, or it was presented alone, with no other lines present on the screen. Displays with and without background lines were grouped in separate blocks of trials. One experimental session contained three blocks of trials. Each block yielded one estimate of the critical ISI for one combination of background condition (present or absent) and target-set size (two, three, or four), in a new random sequence for each session. Each observer served for a total of eight sessions.

Results and Discussion

Critical ISIs, averaged over the four replications, are shown in Figure 3 as a function of target-set size, separately for the 4 observers in the background and no-background conditions. The pattern of results was very similar for all four observers. Critical ISIs were approximately constant as a function of target-set size in the no-background condition (Figure 3a), but increased with set size when the background lines were present (Figure 3b). Linear regressions through the individual points in Figure 3a yielded slopes of 5.7, −7.9, 8.6, and 6.6, for Observers VDL, JK, SZ, and KT, respectively. The corresponding slopes for the condition with background lines (Figure 3b) were 51.1, 9.9, 40.2, and 26.3. Averaged across observers, the slopes for the background condition were steeper than those for the no-background condition by a factor of 9.8, confirming the graphical evidence in Figure 3 that search slopes were substantially steeper when the background lines were present.

What caused the search slopes to be steeper when the background was textured? In answering this question, it is well to be reminded that the orientation-oddball task remained the same, whether the background texture was present or absent. Thus, factors inherent in the oddball-task itself, notably any hypothetical requirements to identify the orientation of the target lines, were common to both background conditions. Being common to both conditions, these factors could not have been wholly responsible for the slope differences seen in Figures 3a and 3b. Incidentally, the mere presence of a background texture does not necessarily mediate steep search slopes. This is confirmed by the results of Experiment 5 and by Folk and Egeth's (1989) study who found that if the background field of diagonal lines is replaced by a field of small circles, the ensuing search slopes are flat. Clearly, factors other than background texture must have intervened in the present experiment.

A coherent picture emerges when the present results are considered jointly with those of Experiment 1 and those of Sagi and Julesz (1985b). The similarity among the three sets of results is remarkable. When the task at hand, whether detection or discrimination, is performed as a single task, the search slopes are flat or shallow. But if the detection or discrimination is performed as part of a dual task, then the search slopes are much steeper. A compelling inference from this pattern of results is that the steepness of the search slope is governed not by whether the task involves identification, as suggested by Sagi and Julesz (1985b), but whether it is performed as a single or dual task.

Although compelling, this conclusion cannot be regarded as definitive without first considering a possible confound, pertaining to the distinction between single and dual tasks. That distinction was explicit in Experiment 1, where the observers were instructed to perform either one task (oddball detection) or two (oddball detection preceded by the judgment of parallelism). However, in Experiment 2, and in our interpretation of Sagi and Julesz's (1985b) experiment, we merely supposed that, when performed against the background of diagonal lines, the discrimination was part of an implicit dual-task sequence. That supposition was buttressed by the experimental outcome. Nevertheless, we must consider the possibility that the functions in Figure 3b may have been steep not because they were obtained in a dual task, but because of some unspecified factor related to the presence of the diagonal background lines. What needs to be shown is that the results illustrated in Figure 3 depend not on the presence or absence of the background lines, but on whether the task is single or dual. This was done in Experiment 3.

Experiment 3

Detection and Discrimination in Single and Dual Tasks

In Experiment 3, all targets were presented within an hexagonal frame, without any background texture. The task at hand, whether detection or discrimination, was performed as either a single task by ignoring the hexagonal frame or as a dual task by preceding it with a judgment of parallelism as in Experiment 1. The design was a 2 × 2 factorial, in which the nature of the task (detection or discrimination) was crossed with task complexity (single or dual).

Two sets of predictions are illustrated in Figure 4. Figure 4a is based on the hypothesis that the steepness of the search slope depends on the nature of the task, as suggested by Sagi and Julesz (1985b): flat functions are expected in detection and steep functions in discrimination, whether the task is single or dual. Figure 4b illustrates the expected pattern of results on the hypothesis that the critical factor is the need to perform an attentional switch between the components of the dual task. In this case, the expected search functions are flat for single tasks and steep for dual tasks, in both detection and discrimination. The empirical outcomes matched the pattern in Figure 4b.

Method

Three authors and 1 naive undergraduate student served as observers in Experiment 3. Apparatus and procedures were the same as in the previous experiments, with the following exceptions. The experiment comprised four conditions, resulting from the factorial combination of the nature of the task (detection or discrimination) and whether the task was single or dual. The basic display pattern is illustrated in Figure 1c. In the single detection condition, observers reported the number of line segments, as in Experiment 1, and ignored the hexagonal frame. In the dual detection condition, observers indicated whether the top and bottom sides of the hexagon had the same orientation, and then they reported on the number of line segments. In the single discrimination condition, observers indicated the presence or absence of an orientation oddball and ignored the hexagonal frame. In the dual discrimination condition, observers indicated whether the top and bottom sides of the hexagon had the same orientation and then reported on the presence or absence of the oddball.

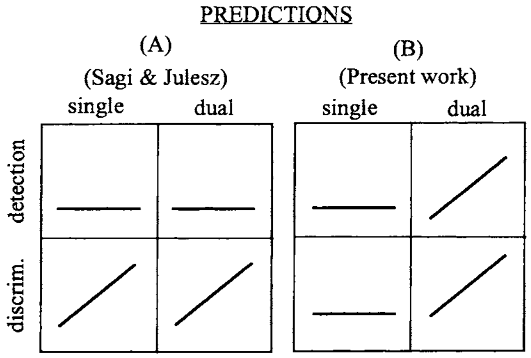

Figure 4. Schematic representation of the predicted search slopes. (A) Slopes predicted on the basis of the nature of the task: flat slopes for detection, steep slopes for discrimination (discrim.), regardless of whether the task is single or dual. (B) Slopes predicted on the basis of task complexity: flat slopes for single tasks, steep slopes for dual tasks, whether detection or discrimination.

Results and Discussion

Critical ISIs, averaged over the four replications, are shown in Figure 5 as a function of target-set size, separately for the 4 observers in all four conditions. The pattern of results was very similar for all 4 observers, whether experienced or naive. Linear regressions through the individual points in Figure 5 yielded the following slopes for Observers VDL, JK, SZ, and YE, respectively: single detection, 4.4, 2.7, 6.8, 5.1; single discrimination, 5.7, −5.9, 10.4, 9.8; dual detection, 89.4, 32.8, 130.6, 22.2; dual discrimination, 94.0, 56.2, 45.0, 38.5. Averaged across observers, the dual-task slopes were steeper than the single-task slopes by a factor of 14.5 in the detection condition and by a factor of 11.7 in the discrimination condition. In the two dual-task conditions, percentages of correct responses in the primary task, in which observers judged whether the top and bottom sides of the hexagonal frame were parallel, were as follows, for Observers VDL, JK, SZ, and YE, respectively: dual detection, 97.7, 92.2, 93.0, 98.4; dual discrimination, 93.4, 93.7, 95.1, 90.5.

The outcome of Experiment 3 is unambiguous: Search slopes were flat in the single-task conditions and steep in the dual-task conditions, whether the task involved detection or discrimination. This pattern of results matches that in Figure 4b, supporting the claim that the slope of the search function depends on whether the task is single or dual, not on whether it involves detection or discrimination.

Without exception, the experiments reported thus far have yielded flat or shallow search slopes in single tasks, but much steeper slopes in dual tasks. This is precisely what would be expected on the basis of dynamic input filtering. Given a dual task, the system should be initially configured optimally for the primary task, and performance on the secondary task should be correspondingly less efficient. A corollary of this approach is that efficiency should suffer mostly in the secondary component of a dual task, not in the first. The outcomes of Experiments 1 and 3 were in line with this expectation. In both experiments, performance on the primary task was invariably well above 90% correct, suggesting that efficiency suffered mostly in the secondary task. However, because set size in the primary task was always constant and small, we cannot be sure. This issue is considered in Experiment 4, where the order of primary and secondary tasks was reversed.

Experiment 4

Reversing the Order of the Tasks

Method

In Experiment 4, we replicated both dual-task conditions (detection and discrimination) of Experiment 3, with the exception that the order of primary and secondary tasks was reversed. Observers (3 authors and 1 naive graduate student) were instructed to give priority to and to report first on the line-segment task, and then to indicate whether the top and bottom

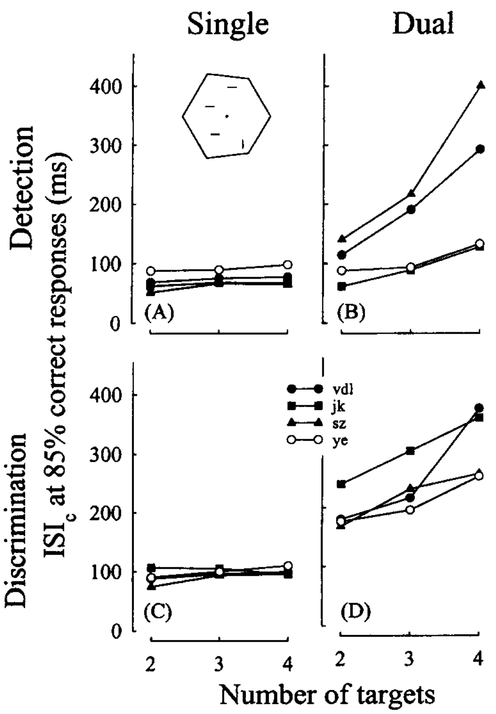

Figure 5. Mean critical interstimulus interval (ISI_c) in Experiment 3. The inset illustrates the display patterns used in all four conditions.

sides of the hexagonal frame were tilted in the same direction. Our plan was to compare the results of Experiment 4 with the corresponding results of Experiment 3. Because the naive observer (GL) had not served in Experiment 3, she also served in two dual-task conditions, corresponding to those in Experiment 3. In all other respects, procedures were the same as in the corresponding dual-task conditions of Experiment 3.

Results and Discussion

Critical ISIs, averaged over the four replications, are shown in Figures 6a and 6c as a function of target set size, separately for the 4 observers in the detection and discrimination conditions. For ease of comparison, the results obtained by the 3 practiced observers in the dual-task conditions of Experiment 3 are presented as segmented lines in Figures 6b and 6d, with the results of the naive observer (GL) presented as continuous lines. Linear regressions through the individual points in Figure 6a yielded the following slopes for Observers VDL, JK, SZ, and GL, respectively: 3.3, −3.1, 6.6, and 9.1. The corresponding slopes in Figure 6c were −2.5, −0.8, 22.7, and 7.4. The slopes of the regression lines through the points of Observer GL in Figures 6b and 6d were 28.0 and 87.0, respectively. Averaged across observers, the slopes in Figure 6b were steeper than those in Figure 6a by a factor of 17.6, and the slopes in Figure 6d were steeper than those in Figure 6c by a factor of 10.5. Percentages of correct responses on the secondary task, in which observers judged whether the top and bottom sides of the hexagonal frame were parallel, were as follows for Observers VDL, JK, SZ, and GL, respectively: detection condition, 94.4, 87.5, 80.0, 95.6; discrimination condition, 88.4, 83.4, 92.2, and 98.4.

Accuracy on the secondary (frame) task in the present experiment was only marginally lower than in Experiments 1 and 3, in which the same task was designated as primary. This parallels the finding in Experiment 1, which revealed only marginal impairment in the secondary task when it was easy. Homologous findings have been reported by Braun and Sagi (1990) and by Braun and Julesz (1998). A common trait of all these studies was that the secondary task was relatively simple and did not involve a complex visual search. Thus, failure to show evidence of dual-task interference in the secondary task may be ascribed to its modest processing requirements. When the processing requirements are increased, as was done in Experiments 1 and 3 by increasing the number of targets beyond two (Figures 2b and 5b), the secondary task is performed inefficiently.

This reveals an intransitivity in the directional effect of difficulty between primary and secondary tasks. An easy first task can cause a second, more difficult task to be performed inefficiently. However, a hard first task does not seem to impair significantly the performance of an easy second task. Clearly, this cannot be explained solely on the basis of absolute task difficulty. On the other hand, the intransitivity is explained naturally on the input-filtering hypothesis. When the visual system is configured optimally for an upcoming easy task, a hard trailing task is performed inefficiently because the system is configured inappropriately. The converse,

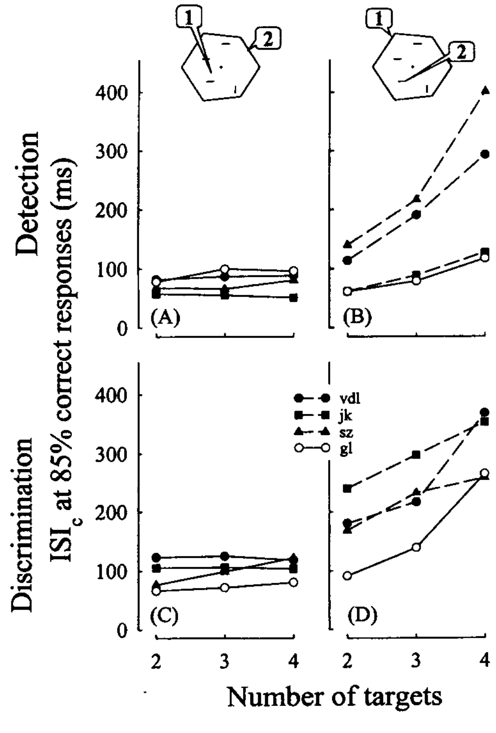

Figure 6. (A) and (C): mean critical interstimulus interval (ISI_c) in Experiment 4. For ease of comparison, the results obtained by the three practiced observers in the corresponding dual-task detection (B) and discrimination (D) conditions of Experiment 3 are presented as segmented lines, with the results of a naive observer (GL) presented as continuous lines. The insets illustrate the display patterns used in the experiments, and indicate the order in which the oddball and the outline tasks were performed.

however, does not hold true because an easy task can be performed with relative efficiency even if the system is not configured optimally for that task. To be sure, if the system is configured optimally for a given task, a trailing task which does not fit that configuration will be performed inefficiently, whether easy or hard. However, if the trailing task is too easy, the difference between efficient and inefficient handling may be too small to affect performance measurably.

The results in Figure 6 provide a clear-cut answer to the question that prompted Experiment 4: Search slopes are steep only for the task that is designated as secondary, always provided that it is suitably hard (Figures 6b and 6d). If the same task is designated as primary, search slopes are shallow or flat (Figures 6a and 6c). This strongly suggests that the relatively inefficient dual-task performance seen in Experiments 1–3 is not a general characteristic of dual tasks, but is largely confined to the task that is done second. We believe this loss of efficiency to be contingent on an inherent attentional switch, with attendant reconfiguration of the input filters, when processing is redirected from the primary to the secondary component of a dual task.

Attentional switching and task-set reconfiguration need not be limited to situations in which the stimuli are presented sequentially. We have argued above that attentional switching may occur when the processing of a single stimulus pattern implicitly requires multiple steps to complete. A similar view is held by Pashler (1999), who noted that "... attempts at simultaneous task performance seem to result in a form of task switching" (p. 30). In the present dual-task procedure, the visual system could be said to be initially configured to optimize performance on the primary task which, therefore, is performed efficiently. However, the same configuration is inappropriate for optimal handling of the secondary task, thus resulting in less efficient performance, indexed by steep search functions. This line of reasoning leads to a testable prediction. If sufficient time were allowed after the primary task for the system to be reconfigured in readiness for the secondary task, then the secondary task should be performed more efficiently. This prediction was tested in Experiment 5.

Experiment 5

Time Out for Reconfiguration

We have argued in the foregoing that Sagi and Julesz's (1985b) discrimination task yielded steep search slopes not because it involved identification but because it was implicitly a dual task. Specifically, we have suggested that, at the outset of a trial, the observer's visual system is optimally configured to perform the primary task, namely, segregation of the target lines from the background texture. That configuration, however, is inappropriate for the secondary task—oddball detection—which, as a consequence, is performed inefficiently. This view implies that if sufficient time were available after texture segmentation for resetting the system to a configuration suitable for oddball detection, then performance on the oddball task should gain in efficiency.

In testing this prediction, our first objective was to separate the two notional components of the discrimination task: texture segmentation from oddball detection. This was done by initiating each trial with a preview pattern in which the locations of the upcoming targets were marked either by addition ("+") signs or by "holes" in the background texture, as illustrated in the insets in Figures 7a and 7b. Although the preview pattern revealed the locations of the upcoming targets, it contained no information as to the actual orientation of the target lines. The "+" signs and the "holes" were regarded as equivalent preview conditions and were presented in separate blocks of trials. During the 500-ms preview period, observers endeavored to perceptually segregate the marked locations from the background texture and then get set for the oddball-detection task. At the end of the preview period, a target set of vertical and/or horizontal line segments was revealed either by deleting one element from each "+" sign or by displaying one line in each of the "holes," depending on the condition. Observers reported on the presence or absence of an orientation oddball in the target set.

In essence, Experiment 5 was a replication of the discrimination conditions in the study of Sagi and Julesz (1985b) and in the present Experiment 2. But there was a key difference. In the present experiment, the preview period allowed observers to make an attentional switch from texture-segmentation to oddball-detection mode. To the extent that success at the discrimination task depended on the implementation of that attentional switch, we expected performance to be more efficient (i.e., search slopes to be shallow) in Experiment 5. The results confirmed this expectation.

Method

Apparatus, methods, and procedures were the same as in Experiment 2, with the following exceptions. Each trial began with a 500-ms preview, consisting of a background pattern of diagonal lines that contained either two, three, or four target locations, as in the previous experiments. There were two preview conditions. In one condition, the target locations contained "+" signs; in the other, the target locations were "holes" in the background texture, as illustrated in the insets of Figures 7a and 7b, respectively. The two preview conditions were grouped in separate blocks of trials. The target lines were presented at the end of the preview period. In the "+" condition, the target lines were produced by removing either the vertical or the horizontal segment in each "+" sign. In the "holes" condition, one target line was displayed in each "hole." The target lines, as well as the background pattern of diagonal lines, remained on display until the arrival of the mask. This was a deviation from the previous experiments, in which the target lines were displayed for only 5 ms. A longer exposure duration was adopted in Experiment 5 because in the "+" condition, the target lines could not be seen if they outlasted the "+" patterns by only 5 ms. Therefore, in the present experiment, the dependent variable estimated by the PEST procedure was the critical stimulus-onset asynchrony (SOA) instead of the critical ISI, as in the previous experiments. Three of the authors and 1 undergraduate student (TK), who was unaware of the purpose of the experiment, acted as observers and reported on the presence or absence of an orientation oddball in the target set, as in Experiment 2. In all other respects, the procedural details of Experiment 5 were the same as in the discrimination-with-background condition in Experiment 2.

Results and Discussion

Critical SOAs, averaged over the four replications, are shown in Figure 7 as a function of target-set size, separately for the 4 observers in the two conditions. Very similar results were obtained by all 4 observers, whether experienced or naive. Critical SOAs remained approximately constant as a function of target-set size in both conditions. Linear regressions through the individual points in Figure 7a yielded slopes of 0.13, 0.88, 0.63, and 3.56 for Observers

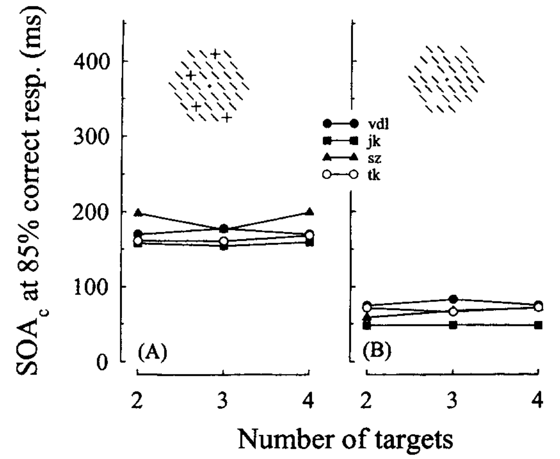

Figure 7. Mean critical interstimulus interval (ISI_c) in Experiment 5. The insets illustrate the display patterns used in the "+" (A) and in the "holes" (B) conditions. SOA_c = critical stimulus-onset asynchrony; resp. = response.

VDL, JK, SZ, and TK, respectively. The corresponding slopes in Figure 7b were 0.06, −0.13, 6.17, and 0.01. The results in Figure 7 should be compared with those in Experiment 2 (Figure 3b) where the same discrimination task was performed without a preview period. Averaged across observers VDL, JK, and SZ (TK had not served in Experiment 2), the slopes in Figure 3b were steeper than those in Figure 7a by a factor of 61.3 and steeper than those in Figure 7b by a factor of 16.9.

Overall, critical SOAs were much longer in the "+" than in the "hole" condition (170.9 vs. 65.1 ms, averaged across observers and set sizes). This echoes the phenomenon known as *attentional capture*, in which suddenly appearing targets are perceived faster than targets formed by deleting parts of an existing pattern (e.g., Yantis, 1993). This difference in mean level between the two conditions, however, has no bearing on the main objective of this experiment because the effect of attentional capture was largely orthogonal to the effect of set size, as shown by the fact that search slopes were flat in both conditions.

Comparison of Experiments 2 and 5 shows that the discrimination task was performed far more efficiently when the target locations were known ahead of time. This finding has important implications for the two theoretical positions that have been juxtaposed throughout the present study. According to Sagi and Julesz (1985b), the discrimination condition yields steep search slopes because it requires identification of the targets' orientations, a time-consuming operation that involves inspection of each target item by focal attention. The finding that search slopes were steep in Experiments 2 but flat in Experiment 5 is problematic for this account because the identification requirement was the same in both experiments, yet performance was more efficient in Experiment 5. It must be emphasized that the preview period, per se, could not have mediated a process of identification because the orientation of the target lines was not revealed until the end of the preview period. Beyond the preview period, the displays in the present experiment were identical to those in Experiment 2 and in Sagi and Julesz's (1985b) study. Clearly, the sharply steeper search slopes seen in Experiment 2, and in Sagi and Julesz's (1985b) study, as compared to the flat slopes in Experiment 5, cannot be explained on the basis of identification requirements alone. Other factors, sensitive to the preview procedure, must have intervened.

Attentional switching appears to be such a factor. We believe that increased search efficiency, following a preview period, is explained naturally if the discrimination task is regarded as being implicitly dual. At the outset of a display sequence, the visual system is configured optimally for dealing with the first component of the dual task, texture segmentation, which is performed efficiently. During the 500-ms delay, the system can then be reconfigured in readiness for the oddball-detection task which, as a consequence, is also performed efficiently. This entire sequence could not be completed in Experiment 2 or in Sagi and Julesz's (1985b) study because there was not enough time for the system to be reconfigured before the arrival of the mask. Thus, texture segmentation was carried out efficiently, but oddball detection was not.

One further issue, related to the role of the background texture of diagonal lines, is addressed by the outcome of the present experiment. In Experiments 2, 3, and 4, the discrimination task yielded flat search slopes, provided that it was carried out as a single task. However, in every case, the target lines were displayed on a featureless background, as distinct from the textured background of diagonal lines, as in the study of Sagi and Julesz (1985b). It may be suggested that the efficient search indexed by flat search slopes was made possible by the absence of the textured background. In other words, it is conceivable that, for unspecified reasons, the presence of a textured background might mediate steep search slopes. This option is disconfirmed by the outcome of this experiment which revealed flat search slopes with targets embedded within a textured background. Instead, this outcome strongly suggests that a textured background mediates steep search slopes only when it creates the need for a first step in an implicit dual-task sequence, namely, when it creates the need for texture segmentation in close temporal contiguity with the oddball-detection task. When that temporal contiguity is obviated, as in the present experiment, search slopes are flat, even in the presence of a textured background.

General Discussion

Two conceptions of early vision were compared in the present work: a hard-wired preattentive system versus a programmable system controlled by higher brain regions. The two conceptions were juxtaposed in five experiments using detection and discrimination tasks within a visual search paradigm. In the detection task, observers reported on the number of oddly oriented lines in the display. In the discrimination task, they reported on the presence or absence of an orientation oddball within the target set. According to the two-stage conception, exemplified in the work of Sagi and Julesz (1985a, 1985b), detection is carried out by built-in units at a preattentive stage where processing is done in parallel, as evidenced by flat or shallow search slopes.

Discrimination, on the other hand, is said to require identification of the lines' orientation, a process that requires serial attentive scrutiny, as evidenced by steep search slopes. We put forward an alternative hypothesis that the steepness of the search slope is determined not by the nature of the task (detection vs. discrimination) but by whether the task involves an attentional switch (single vs. dual task). In Experiment 1, a detection task yielded either shallow or steep slopes, depending on whether it was carried out as a single or as a dual task. A similar outcome was obtained in Experiment 2 with a discrimination task. The two hypotheses were contrasted in Experiment 3, where detection and discrimination were crossed with single and dual tasks in a 2 × 2 design. The steepness of the resulting search slopes depended not on the nature of the task but on whether it entailed an attentional switch. Experiment 4 showed that the relatively low efficiency seen in dual tasks is largely confined to the task that is done second. But even the second task can be performed efficiently if a sufficient period of time is allowed to elapse after the first task, as was done in Experiment 5.

This pattern of results is inconsistent with the claim that the need for focal attention, as indexed by a steep search slope, depends on the nature of the task. Instead, the present results indicate that detection and discrimination tasks can yield either flat or steep slopes, depending on whether they are performed as single or dual tasks. We conclude that the key factor in determining the efficiency of early visual processing lies not in the nature of the stimuli or tasks, but in whether they can be handled optimally by the current configuration of the input system.

Dynamic Control in Early Vision

Stemming from this conclusion is a conception of early vision that differs sharply from the two-stage model outlined in the introductory section. In that model, initial processing is carried out by built-in units at a preattentive stage, controlled exogenously by incoming stimuli. This is a relatively impliable, hard-wired model of early vision. Instead, we propose a malleable system whose components can be quickly reconfigured to perform different tasks at different times, much as the internal pattern of connectivity in a computer is rearranged dynamically by enabling and disabling myriads of gates under program control. In such a system, descending signals from higher centers can reconfigure the same neurons at the lower levels to perform very different functions at different stages in the processing cycle. This is a form of true multiplexing, which is concordant with the available neurophysiological evidence (e.g., Bridgeman, 1975, 1980; Gilbert & Wiesel, 1989; Lamme, Zipser, & Spekreijse, 1997; Sillito, Jones, Gerstein, & West, 1994) and permits a leaner, more efficient system than one with enough neurons to do the same job in a hard-wired fashion. Psychophysical evidence and a computational model consistent with this approach have been presented by Di Lollo, Enns, and Rensink (2000).

This conception of the visual system can be likened to a system of filters that are dynamically reconfigured so as to deal most efficiently with the expected input. Filtering mechanisms may involve both central and peripheral areas in the visual brain. For example, attending selectively to stimuli in motion is likely to comprise gating circuitry in cortical areas V1 and V5. Other candidate areas are those that have direct excitatory or inhibitory links with prefrontal cortex. This may include subcortical structures such as the perigeniculate nucleus, which is known to receive direct excitatory input from prefrontal cortex (Skinner & Yingling, 1977; Steriade, Domich, & Oakson, 1986). To function effectively, the filtering system must be responsive to changes in attentional set and in response planning associated with rapidly sequential stimuli or multitasking requirements. These are control functions normally associated with high-level structures in prefrontal cortex (Goldman-Rakic, 1987, 1988). That prefrontal cortex is critically involved in the establishment and maintenance of attentional sets is indicated by striking failures of selective attention in frontal lobe patients (Shallice, 1988).

This is not to say that input filters can be configured to any arbitrary level of complexity. Indeed, the literature on visual search reveals definite constraints. For example, it is known that feature searches (e.g., searching for a red "T" among green "Ts") yield efficient shallow slopes, whereas conjunction searches (e.g., searching for the same red "T" among green "Ts" and red "Ls") yield inefficient steep slopes. On the face of it, this may suggest that the system can be configured to deal efficiently with feature searches but not with conjunction searches. Such a constraint resembles that encountered in feature-integration theory (Treisman & Gelade, 1980). However the present account differs from feature-integration theory in at least two important ways. First, the built-in analyzers postulated in feature-integration theory are replaced by flexible, programmable input filters, as illustrated in the present experiments. Second, efficient processing is not limited to simple features such as color or orientation. Rather, input filters can be configured to process efficiently such complex displays as 3-D objects, surface shapes, and letters of various fonts. The present need is for a systematic investigation of the constraints that govern the complexity to which input filters can be configured. In so doing, one must bear in mind that any given conjunction search may involve an implicit task switch. In the above example of "Ts" and "Ls," the conjunction task may involve a switch between form and color attributes. If the system cannot be reconfigured in time, the task will be performed serially and inefficiently, as was the case in Sagi and Julesz's (1985b) discrimination task.

Nor is it the case that configuration of the input filters can always be achieved in full measure by endogenous signals alone. The evidence suggests that exogenous input may also be required. This was shown in a study by Rogers and Monsell (1995, Experiment 6), in which a task switch was implemented between a run of trials in which the target was a letter and another run in which the target was a digit. The results revealed a substantial deficit on the first trial following a switch, with no further improvement after the second trial. This was the case even when the interval between the two tasks was sufficient for the system to be reconfigured. On the basis of these results, Rogers and Monsell (1995) concluded that ". . . although task-set reconfiguration can be initiated endogenously, the exogenous trigger of a stimulus attribute associated with a task is needed to complete the process of reconfiguring" (p. 226). To be sure, a substantial degree of reconfiguration can be achieved even without an exogenous trigger, as was shown by Meiran (1996) and by the present work. What remains to be determined, however, is whether an exogenous trigger is required to complete the process of reconfiguration under all display conditions.

An even more detailed glimpse into the nature of input filtering is offered by studies in which transcranial magnetic stimulation (TMS) was used to explore the processes involved in visual search. In a study by Ashbridge, Walsh, and Cowey (1997), observers performed either a feature search that yielded efficient shallow slopes (find a green vertical bar amongst green horizontal bars) or a conjunction search that yielded inefficient steep slopes (find a green vertical bar amongst green horizontal and blue vertical bars). Application of TMS over parietal visual cortex interfered with the conjunction search but not with the feature search. This suggests that what is disrupted by TMS is the inefficient serial processing in which signals from higher visual areas, such as parietal cortex, are iteratively compared with ongoing activity at lower levels. By the same token, the finding that feature search was unaffected by TMS over parietal cortex is consistent with the notion that the efficient input filter is implemented at an early stage of visual information processing.

Further details about the mechanisms of input filtering are revealed by studies in which TMS procedures were combined with perceptual learning. In a study by Walsh, Ashbridge, and Cowey (1998), observers received extensive training on a conjunction search that initially yielded an inefficient steep slope. By the end of training, the search was performed efficiently, as evidenced by a flat slope. The important finding was that application of TMS over parietal visual cortex disrupted search performance before but not after training. This prompts the hypothesis that extended training may promote the establishment of an input filter capable of handling conjunction searches as though they were feature searches. In the words of Walsh et al. (1998), extended training may create a new template that "... would enable a search that was previously serial to become parallel and therefore would not require attentional engagement and feature binding mediated by the parietal cortex" (p. 366). Especially revealing was the finding that the effect of TMS was reinstated even after extensive training if some attribute of the search display was changed. This suggests that the structure of the input filter is highly specific to the features contained in the training stimulus and not to the cognitive operations common to all conjunction search tasks. It should also be noted, at least in passing, that perceptual learning of this kind is problematic for models based on built-in preattentive analyzers but is explained naturally in terms of programmable input filters.

Related Brain-Imaging Evidence

Mounting evidence from brain-imaging studies is strongly supportive of this conceptual framework. Attentional modulation of activity in areas as peripheral as primary visual cortex has been reported by Somers, Dale, Seiffert, and Tootell (1999), who found that the cortical response in area V1 is enhanced for attended stimuli and is suppressed when attention is directed elsewhere. These findings have been confirmed by Martinez et al. (1999), who, by combining fMRI and ERP measures, were able to relate the low-level modulation to signals from higher visual areas. In the same vein, recent studies by Corbetta, Kincade, Ollinger, McAvoy, and Shulman (2000) and by Hopfinger, Buonocore, and Mangun (2000) obtained patterns of brain activity entirely consistent with the present thesis that signals from higher regions regulate the processing of sensory input in primary visual cortex.

Perhaps the strongest support for the present thesis, however, comes from studies in which patterns of brain activity were recorded not in response to external stimuli, but to the mere expectation of impending stimulation (Gandhi, Heeger, & Boynton, 1999; Kastner, Pinsk, De Weerd, Desimone, & Ungerlider, 1999). These studies revealed specific patterns of anticipatory activity as peripherally as primary visual cortex, in the absence of visual stimulation. Homologous modulation of cortical activity in the absence of external input has been reported in the auditory domain (Nusbaum et al., 1999). In that study, the pattern of brain activity varied as a function of the participant's expectation, and it extended as peripherally as primary auditory cortex. This is not to say that input filtering is mainly a peripheral process. That higher levels are also involved is strongly suggested by the findings that initial filtering may involve such advanced functions as lexical and semantic processing (Luck, Vogel, & Shapiro, 1996; Maki, Frigen, & Paulson, 1997; Visser, Merikle, & Di Lollo, 1998).

Collectively, these studies reveal precisely the type of anticipatory brain activity that would be expected on the basis of a flexible input system whose components operate concurrently and interdependently under the control of higher centers, and are dynamically reconfigured to meet the processing demands of the task at hand. This emphasis on the functional characteristics of early vision, as distinct from its structural properties, deviates sharply from the built-in preattentive stage postulated in the two-stage model. Rather, our proposal is in line with the idea that visual perceptions emerge not from a series of discrete feed-forward stages, but from iterative exchanges between higher and lower brain regions through reentrant pathways, with primary visual cortex being critically involved in all successively higher levels of computation (Di Lollo et al., 2000; Lee, Mumford, Romero, & Lamme, 1998; Motter, 1993). This conception is congruent with current models of cortical functioning, which suggest that abstract representations of objects and patterns stored at higher levels are fit to incoming stimuli at lower levels (Hayhoe, 2000; Rao & Ballard, 1997). It should also be noted, at least in passing, that these views are entirely compatible with the main tenets of Wolfe's concept of *guided search*, in which the efficiency of visual search is set by descending signals from higher brain regions, which modulate processing activity at the lower levels (Wolfe, 1994; Wolfe, Cave, & Franzel, 1989).

Related Behavioral Evidence

As well as being consistent with the neurophysiological and brain-imaging evidence, the present scheme is in line with the outcomes of related behavioral studies. Our claim that efficient processing depends on the adequacy of the preparatory set is entirely consistent with a phenomenon known as *contingent capture*, in which a new stimulus is automatically processed even though it is not a target, if its defining features (e.g., color, abruptness of onset) belong to the same class as those expected in the upcoming display (Bacon & Egeth, 1994; Folk, Remington, & Johnston, 1992; Folk, Remington, & Wright, 1994; Gibson & Kelsey, 1998). On the present scheme, such a stimulus is automatically processed because it fits the current configuration of the input filters.

If a new stimulus arrives while the system is not suitably configured, at least two options are available. On one option, the stimulus is stored as a low-level representation and processing is postponed while the system is reconfigured. Evidence for such a postponement has been reported by McCann, Remington, and Folk (1999), and the time course of reconfiguration has been studied by Meiran (1996). Following such a postponement, the stimulus is processed efficiently because the system has been suitably reconfigured. Alternatively, if the system cannot be reconfigured in time, the new stimulus must be processed, using the extant ill-suited configuration. In this case, processing is inefficient as indicated by steep search slopes, suggestive of serial scrutiny. An extreme example of this kind of inefficiency is a phenomenon known as *inattentional blindness*, in which a stimulus may be missed altogether if it arrives unexpectedly (Mack & Rock, 1998).

We conclude by explicitly rejecting the notion of a hard-wired, stimulus-bound preattentive stage of processing. Further, we suggest that the very question concerning "need for attention" may be ill-posed. The key issue is not whether a given processing activity, such as detection or discrimination, or a given class of stimulus features, such as simple or conjoint, requires attention. Rather, the issue is whether or not the visual system is configured optimally for the task at hand.

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