System reconfiguration, not resource depletion, determines the efficiency of visual search

VINCENT DI LOLLO

Simon Fraser University, Burnaby, British Columbia, Canada

DANIEL SMILEK

University of Waterloo, Waterloo, Ontario, Canada

JUN-ICHIRO KAWAHARA

Hiroshima University, Hiroshima, Japan

and

S. M. SHAHAB GHORASHI

University of British Columbia, Vancouver, British Columbia, Canada

We examined two theories of visual search: *resource depletion*, grounded in a static, built-in brain architecture, with attention seen as a limited depletable resource, and *system reconfiguration*, in which the visual system is dynamically reconfigured from moment to moment so as to optimize performance on the task at hand. In a dual-task paradigm, a search display was preceded by a visual discrimination task and was followed, after a stimulus onset asynchrony (SOA) governed by a staircase procedure, by a pattern mask. Search efficiency, as indexed by the slope of the function relating critical SOA to number of distractors, was impaired under dual-task conditions for tasks that were performed efficiently (shallow search slope) when done singly, but not for tasks performed inefficiently (steep slope) when done singly. These results are consistent with system reconfiguration, but not with resource depletion, models and point to a dynamic, rather than a static, architecture of the visual system.

Visual search is something we do routinely every day: We select a specific key from a bunch on our key chain, and we pick a coin for the parking meter from a handful of coins. Laboratory studies have had the aim of discovering the rules that govern visual search and identifying the factors that affect its efficiency. Observers are typically required to search for a given target (e.g., the letter T) among distractors (e.g., other letters). In attentionally demanding tasks, it is usually the case that the time to find the target (reaction time, RT) increases with the number of distractors. Efficiency of visual search, therefore, is indexed by the slope of the function relating RT to the number of distractors. The shallower the slope, the more efficient the search. The term *efficiency* is used throughout the present article in a strictly descriptive sense. In

this respect, we follow Wolfe's (1998) practice of drawing an explicit distinction between the empirically descriptive term *efficiency* and other, more theoretical terms that have been used to relate the efficiency of visual search to various theoretical constructs, such as the distribution of attention.

In the present work, we examined two contrasting views of the role of attention in visual search: the *resource depletion* hypothesis, in which attention is seen as a resource that can be depleted when deployed to one or more tasks, and the *system reconfiguration* hypothesis, in which attention is thought to be a process by which the visual system is dynamically reconfigured to optimize performance on the task at hand. Specifically, we used a dual-task paradigm to determine whether the efficiency of visual search is affected by the requirement to process another stimulus presented directly before the search display. In juxtaposing the two models, our broader aim was to generalize the experimental outcome beyond the confines of visual search to the general issue of how information is handled within the visual system.

The Resource Depletion Hypothesis

Central to the resource depletion hypothesis is some form of limited attentional resource that is depleted when distributed among multiple stimuli or tasks. In this model, the efficiency of visual search is said to be related to the

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need for attentional resources. Tasks that yield efficient shallow slopes are said to be carried out *preattentively*—namely, with little or no drain on attentional resources. Preattentive processing is thought to be performed by built-in analyzers that respond automatically to specific stimulus attributes, such as color, orientation, and spatial frequency. In contrast, tasks that yield inefficient steep slopes are said to require the deployment of—and to be a drain on—attentional resources (for a review, see Wolfe, 1998).

Within this conceptual framework, tasks that can be done preattentively and tasks that require focused attention are affected differently under dual-task conditions. If the task is carried out preattentively, then, by definition, it does not deplete attentional resources. Search efficiency, therefore, should not be affected when attention is deployed concurrently to another task. In contrast, if the task requires focused attention, search efficiency should suffer to the extent that attentional resources are deployed to the other task (but see Pashler, 1989). Thus, dual-task requirements should cause the inefficient steep slope of an attentionally demanding search task to become steeper but should leave the efficient shallow slope of a preattentive task virtually unaffected.

The System Reconfiguration Hypothesis

An alternative account stems from a dynamic model of attentional control, which differs sharply from the resource depletion model. Instead of static built-in analyzers that respond automatically and preattentively, the reconfiguration model postulates a malleable system that can be quickly reconfigured to perform different tasks at different times. 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. Monsell (1996) has referred to this process as *task set reconfiguration*; William James (1890/1950) termed it *ideal preparation or adaptation of attention*.

This conception of visual functioning can be likened to a system of filters that are dynamically reconfigured so as to deal most efficiently with the expected input. Stimuli that fit the characteristics of the input filter are handled efficiently, yielding shallow search slopes. Other stimuli are handled less efficiently and yield correspondingly steeper search slopes (Di Lollo, Kawahara, Zuvic, & Visser, 2001; Kawahara, Zuvic, Enns, & Di Lollo, 2003; Visser, Bischof, & Di Lollo, 1999).

Efficiency of visual search, therefore, is said to depend on whether the system can be configured optimally for a given single task. It must be emphasized, however, that the system cannot be configured to function efficiently (i.e., to yield shallow search slopes) for any arbitrary task. Indeed, the literature on visual search reveals definite constraints on the range of tasks for which this can be done. For example, one constraint is encountered when the target is defined by a conjunction of features (e.g., color and shape), each of which is also present in some of the other item in the search array. The limit of complexity

to which the system can be configured remains to be established. It is clear, however, that efficient shallow search slopes can be obtained with such complex images as three-dimensional objects, surface shapes, and letters of various fonts and sizes, which are too complex to be handled by the built-in analyzers postulated in the preattentive hypothesis (Wolfe, 1998).

Comparing the Two Hypotheses

We compared predictions from the system reconfiguration and the resource depletion hypotheses under conditions in which attention was distributed over time, rather than across space, as in more conventional visual search studies. To distribute attention over time, we presented two brief targets in rapid succession. It is commonly found that, under these display conditions, identification accuracy for the trailing target is substantially impaired (Pashler, 1998). Divergent predictions from the two hypotheses can then be tested by varying the temporal interval (stimulus onset asynchrony, SOA) that elapses between the leading and the trailing components of a dual task.

Predictions from the system reconfiguration hypothesis. First, consider a task that is performed efficiently (shallow search slope) as a single task. Suppose that an observer is required to process two different stimuli presented at a very short SOA and that the trailing stimulus involves a task that is performed efficiently as a single task. From the standpoint of dynamic input filtering, the system is initially configured optimally for the leading task, which it will perform efficiently, but not for the trailing task, which it will perform inefficiently. Thus, a task that is performed efficiently when done as a single task will be performed inefficiently if it is done directly after another task. In contrast, if a sufficiently long SOA elapses between the two tasks, the system can be suitably reconfigured during that interval, and the trailing task will again be performed efficiently and will exhibit a correspondingly shallow slope.

Next, consider a task that is performed inefficiently (steep search slope) as a single task. According to the system reconfiguration hypothesis, such a task is performed inefficiently because the system cannot be suitably configured. Therefore, the task should continue to be performed just as inefficiently when preceded immediately (short SOA) by a different task, because, within this theoretical framework, efficiency depends not on the depletion of a limited resource, but on whether the system can be configured optimally for that task. By the same token, the insertion of a long SOA should not improve efficiency, because the system cannot be configured to perform that task efficiently even as a single task.

Predictions from the resource depletion hypothesis. Diametrically opposite predictions are generated by the resource depletion hypothesis. If the trailing task can be done preattentively, it should always be done efficiently, because there is no drain on attentional resources, regardless of SOA. If the trailing task requires focused attention, however, inserting a long SOA should be of benefit, because the leading task could be completed dur-

ing the SOA, thus allowing attentional resources to be deployed entirely to the trailing task. In this case, search efficiency will improve, and the search slope will be correspondingly shallower. These predictions are examined in Experiment 1.

Some of the contrasting predictions from the two models outlined above were examined in an earlier study (Di Lollo et al., 2001). That study, however, was concerned exclusively with tasks that are performed efficiently as single tasks. As we have seen, however, the resource depletion and the system reconfiguration models generate contrasting predictions also with regard to tasks that are performed inefficiently when done singly. The present work builds on the experiments of Di Lollo et al. by testing predictions involving search tasks that are performed inefficiently as single tasks. As such, the present work encompasses the entire range of theoretical predictions concerning efficient and inefficient tasks within a single study. In addition, whereas in the study of Di Lollo et al. (2001a), trained psychophysical observers were used, naive observers were used in the present study, in order to broaden the generality of the findings across populations of observers.

EXPERIMENT 1

All the observers performed a dual task. The first component consisted of a briefly presented hexagonal outline, as illustrated in Figure 1A. The top and bottom lines of the hexagon were always tilted away from the horizontal, clockwise or counterclockwise. The observers reported whether the two lines were parallel or diverging. The second component consisted of one of two search tasks that, when done singly, yielded either efficient shallow slopes or inefficient steep slopes, respectively. The display in the efficient task consisted of between one and four briefly presented line segments, with the observers reporting the number of segments. This is a subitizing task known to yield efficient shallow slopes as a single task (Di Lollo et al., 2001; Sagi & Julesz, 1985). Henceforth, we will refer to this as the *subitizing* (SUB) task.

In the inefficient search task, the target consisted of the letter T, rotated 90° clockwise or counterclockwise, with observers reporting its orientation. Each display also contained between one and three distractors, consisting of the letter L oriented randomly. This task, henceforth referred to as the *T/L* task, is known to yield inefficient steep slopes as a single task (Duncan & Humphreys, 1989; Wolfe, Cave, & Franzel, 1989). The SOA between the two components was either 200 or 700 msec. In selecting the shorter SOA, our intent was to ensure that the leading stimulus had not been fully processed by the time the trailing stimulus was presented. Thus, the experimental design was a $2 \times 2 \times 3$ factorial, with two between-subjects factors (task [SUB vs. T/L]) and duration of SOA [200 vs. 700 msec], and one within-subjects factor (number of distractors, at three levels).

Figure 1. Schematic representation of the hexagonal frame, line segments, and the trailing mask used in the present experiments.

Method

Forty-eight undergraduate students were assigned randomly to four groups of 12 observers each. The four groups corresponded to the four between-subjects cells of the factorial design and were denoted, in terms of the task and the SOA, as follows: SUB-200, SUB-700, T/L-200, and T/L-700.

The stimuli were displayed on a Tektronix 608 oscilloscope equipped with P15 phosphor, viewed from a distance of 57 cm, set by a headrest. Each trial began with a small fixation cross in the center of the screen and was initiated 500 msec after the observers pressed the space bar. The display sequence began with the hexagonal outline (diameter = 7.5°, line thickness less than 0.1°) presented for 10 msec, centered on fixation. The top and bottom lines of the hexagon were tilted 14° away from the horizontal, clockwise or counterclockwise, at random. After the appropriate SOA (200 or 700 msec), the search display was presented for 10 msec. In the two SUB conditions, the search display contained between one and four line segments 0.8° long and less than 0.1° thick, randomly oriented either vertically or horizontally and distributed randomly within an imaginary circle of 6.5° diameter, centered on fixation. In the two T/L conditions, the search display consisted of the letter T rotated 90° clockwise or counterclockwise, at random, and between one and three letter L distractors oriented randomly. The T and Ls were distributed randomly within an imaginary circle of 6.5° diameter, centered on fixation. In all four conditions, the display sequence continued with a variable temporal gap, described below, during which the screen remained blank. The display sequence terminated with a 10-msec presentation of a masking pattern consisting of 36 randomly rotated Vs grouped within an imaginary circle of 6.5° diameter, centered on fixation, as is illustrated in Figure 1B. The luminance of the displays was set at a relatively high 200 cd/m², to compensate for the brief exposure durations (Bloch's law). This made the displays comfortably visible.

In the two SUB conditions, the observers reported the number of line segments. In a given block of trials, the number of line segments was fixed at (1) one or two, (2) two or three, or (3) three or four. Within each block, the observers pressed the left arrow key to indicate the lesser number of targets and the right arrow key for the greater number. Within a block, the lesser and greater numbers of target lines were presented randomly and with equal probability. In the two T/L conditions, the observers indicated the orientation of the target T by pressing either the Z key or the X key for left or right tilt, respectively. In any given block of trials, the number of L letter distractors was fixed at one, two, or three.

A dynamic threshold-tracking procedure (PEST; Taylor & Creelman, 1967) was used to converge on the critical duration of the temporal gap between the search display and the trailing mask at which the observers made approximately 85% correct responses.

Three such estimates were obtained for each observer, one for each number of distractors, with order counterbalanced across observers. On any given trial, the observers responded first to the hexagon task, which was designated as the primary task to which the observers were instructed to pay full attention. The fact that mean accuracy on this task was 90% indicates that the observers complied with instructions.

Results and Discussion

Mean durations of the critical gap are shown in Figure 2. The data were analyzed in a $2 \times 2 \times 3$ analysis of variance (ANOVA) with task (SUB vs. T/L) and SOA (200 vs. 700 msec) as between-subjects factors and number of distractors as a within-subjects factor. The analysis revealed significant effects of task [$F(1,44) = 44.13$, $MS_e = 7,550.51$, $p < .001$] and set size [$F(2,88) = 42.68$, $MS_e = 3,526.87$, $p < .001$]. The set size $\times$ task interaction was also significant [$F(2,44) = 8.37$, $MS_e = 3,526.87$, $p < .001$], confirming that the search slopes, averaged across SOA, were shallower in the SUB task than in the T/L task. Notably, the difference between the 200- and the 700-msec search slopes was greater in the SUB than in the T/L condition, as is shown by the significant linear component of the three-way interaction among task, SOA, and set size [$F(1,44) = 4.80$, $MS_e = 1,366.59$, $p < .05$]. No other effects were significant.

In brief, the predictions can be restated as follows. According to the resource depletion model, search slopes in the SUB task should be shallow and unaffected by the SOA, whereas slopes in the T/L task should be steep at the short SOA and shallower at the longer SOA. Diametrically opposite predictions were derived from the system reconfiguration model: Search slopes in the SUB task should be steeper at the shorter SOA than at the longer

SOA; in the T/L task, slopes should be unaffected by the SOA. The pattern of results in Figure 2 and the results of the statistical analysis—notably, the significant three-way interaction—disconfirm the resource depletion model but are entirely consistent with the system reconfiguration model. The results in Figure 2A are consistent with—and broaden the generality of—the results obtained in an earlier study (Di Lollo et al., 2001) in which trained psychophysical observers were used.

Before reaching a definitive conclusion regarding the failure of the resource depletion model, however, we need to consider two possible reasons for the model's inability to predict the present results. First, it may be argued that the T/L task might be so attentionally demanding that it requires virtually full attention. That is, performance of the T/L would be impossible unless *all* attentional resources were available for it. On this option, the T/L task could not be performed concurrently with another task while even a minimal amount of attentional resources was deployed to the other task. In this case, search efficiency would be the same at both the short and the long SOAs, but the mean duration of the critical gap would be longer at the shorter SOA. This is because, in order to be given full attention, the T/L task would have to be postponed at the shorter SOA, while at least some attention was still deployed to the leading task. On this assumption, the parallel functions in Figure 2B could be explained by the resource depletion hypothesis. This assumption, however, is ad hoc and is not supported by related findings in the literature. For example, Jiang and Chun (2001) found that the spatial structure of a display could be successfully encoded even while the observer was performing a T/L search task. Notably, Jiang and Chun's display contained

Figure 2. Mean durations of critical gap in Experiment 1. In the subitizing counting task, observers reported the number of line segments presented in the display. In the T/L task, they reported on the orientation of a letter T tilted 90° clockwise or counterclockwise.

16 items, as distinct from the present 2–4 items, yet the amount of residual resources available while the T/L task was performed was sufficient to support the concurrent processing of other stimuli.

The second possible reasons for the resource depletion model's inability to predict the present results is that in the T/L task, an SOA of 700 msec may not have been sufficient to complete the processing of the hexagonal outline and to redeploy attention to the trailing search task. The attendant dearth of attentional resources would cause the T/L task to be done inefficiently even at the longer SOA. What needs to be shown is that the T/L task is performed at the same level of efficiency when it is done as a single task as when it is preceded by the hexagon task 700 msec earlier. This was done in Experiment 2, in which both the T/L and the SUB tasks were presented as single tasks.

EXPERIMENT 2

Method

Twenty-four new observers participated in Experiment 2. The stimuli and procedures were the same as those in the 700-msec condition in Experiment 1, except that the observers were instructed to ignore the leading hexagonal frame. Thus, Experiment 2 employed a 2 (task: SUB vs. T/L) $\times$ 3 (number of distractors) factorial design.

Results and Discussion

Mean durations of the critical gap are shown by the triangular symbols in Figure 3. An ANOVA revealed significant effects of task [$F(1,22) = 21.04$, $MS_e = 5,384.34$, $p < .001$] and set size [$F(2,44) = 14.65$, $MS_e = 1,498.48$, $p < .001$]. The set size $\times$ task interaction was also significant [$F(2,44) = 6.45$, $MS_e = 1,498.48$, $p < .001$].

To check whether the efficiency of visual search differed between Experiment 2 and the corresponding 700-msec SOA conditions in Experiment 1 (shown in Figure 3 by the circular symbols), we performed an ANOVA on the combined results, with experiment (1 or 2) as a between-subjects factor. The analysis revealed significant effects of task [$F(1,44) = 46.43$, $MS_e = 6,236.30$, $p < .001$], set size [$F(2,88) = 33.98$, $MS_e = 1,532.79$, $p < .001$], and experiment [$F(1,44) = 7.96$, $MS_e = 6,236.30$, $p < .01$]. The set size $\times$ task interaction was also significant [$F(2,88) = 16.38$, $MS_e = 1,532.79$, $p < .001$], suggesting that the SUB task was performed more efficiently than the T/L task. No other effects—notably, any of the interactions involving experiment—were significant, confirming the evidence in Figure 3 that the curves within each panel were essentially parallel. This is consistent with the claim that the efficiency of visual search in the T/L condition in Experiment 1 was not affected by the requirement to perform the hexagon task 700 msec earlier.

The results of Experiment 1 are pertinent to another issue regarding search efficiency. By comparing Experiments 1 and 2, it is possible to assess the role of memory load on the efficiency of visual search, an issue first addressed by Woodman, Vogel, and Luck (2001). In Experiment 1, we studied efficiency of visual search as a function of SOA. Regardless of SOA, however, the observers carried a memory load in each of the four conditions, because they had to remember the orientation of the hexagon lines while performing the visual search. In contrast, there was no memory load in Experiment 2. In Figure 3, the results of Experiment 2 are compared with the corresponding 700-msec conditions in Experiment 1. The parallel func-

Figure 3. Mean durations of the critical gap in Experiment 2 (triangular symbols). The results of Experiment 1 (circular symbols) have been entered into the figure for ease of comparison.

tions in Figure 3 replicate closely the results of Woodman et al., who found that a memory load impairs the overall performance, but not the efficiency, of visual search.

In agreement with the suggestions of Woodman et al. (2001), the memory load in Experiment 2 may have delayed the onset of the search process, thus increasing the duration of the temporal gap at which the search display could escape masking. This raised the intercept of the functions (Figure 3, circular symbols) but did not affect search efficiency, as indexed by the slopes of the functions. In accord with this hypothesis, memory load increased the intercepts of the SUB and the T/L functions in about equal measure.

EXPERIMENT 3

In Experiments 1 and 2, a SUB task (which was performed efficiently as a single task) was used in conjunction with a T/L search task (which was performed inefficiently as a single task) to test theoretical predictions regarding the effect of SOA on search efficiency. A tacit assumption was that the two tasks, although differing in efficiency, were comparable in respect to other salient characteristics. The tenability of this assumption, however, could be questioned, because the two tasks differ substantially from one another. It may be argued, for example, that the SUB task may not share the characteristics of more conventional search tasks, such as the T/L task. On this option, the pattern of results obtained in Experiment 1 (Figure 2) might be ascribable not to differences in efficiency, but to other, intrinsic differences between the two tasks.

This option was examined in Experiment 3, in which the SUB task was replaced by a more conventional search

task involving the detection of an oddly oriented line segment. In addition, we replaced the 200-msec SOA condition with a 0-msec SOA condition in which the hexagonal outline and the line segments were presented simultaneously. This was done to maximize the attentional demands imposed by the dual-task requirements. Thus, the design of Experiment 3 was a $2 \times 2 \times 3$ factorial, with two between-subjects factors (task [oddball vs. T/L]) and duration of SOA [0 vs. 700 msec] and one within-subjects factor (number of elements, at three levels: two, three, or four). The three groups of observers in the present experiments were assigned to three of the four between-subjects cell of the factorial design (0- and 700-msec SOA oddball, and 0-msec SOA T/L. The fourth cell (700-msec SOA T/L) was filled by the corresponding condition from Experiment 1.

Method

Thirty-six new observers participated in Experiment 3. They were allocated randomly to three groups of 12 observers each. Two groups performed the oddball task, in which the observers viewed the same displays as those in the SUB task in Experiment 1 but performed an oddball task instead of the SUB task. Specifically, the display contained an hexagonal outline and two, three, or four line segments. On half the trials, all the line segments had the same orientation, and on the other half of the trials, one segment was oriented orthogonally to the other segments. The observers performed the hexagon task as in Experiment 1 and then indicated whether or not the line segments contained an orientation oddball by pressing the appropriate arrow keys on the keyboard. For one group of observers (the 0-msec SOA oddball group), the SOA between the hexagonal outline and the line segments was equal to zero. For the other oddball group (the 700-msec SOA oddball group), the SOA was 700 msec. The condition for the third group of observers (the 0-msec SOA T/L group) was the same as the T/L 200-msec condition in Experiment 1, except that the SOA was equal to zero.

Figure 4. Mean durations of the critical gap in Experiment 3. In the oddball task, the observers reported the presence or absence of an oddly oriented line segment presented in the display. In the T/L task, they reported on the orientation of a letter T tilted 90° clockwise or counterclockwise.

Results and Discussion

Mean durations of the critical gap are shown in Figure 4. The data were analyzed in a $2 \times 2 \times 3$ ANOVA with task (oddball vs. T/L) and SOA (200 vs. 700 msec) as between-subjects factors and number of elements as a within-subjects factor. The analysis revealed significant effects of SOA [$F(1,44) = 59.51$, $MS_e = 914,058.69$, $p < .001$] and of number of elements [$F(2,88) = 23.07$, $MS_e = 170,557.49$, $p < .001$]. There were three significant interactions: task $\times$ SOA [$F(1,44) = 4.40$, $MS_e = 67,493.88$, $p < .05$], SOA $\times$ number of elements [$F(2,88) = 4.87$, $MS_e = 36,027.35$, $p = .01$], and task $\times$ SOA $\times$ number of elements [$F(2,88) = 6.89$, $MS_e = 50,944.27$, $p < .005$]. No other effects were significant. Notably, the significant three-way interaction among task, SOA, and number of elements mirrors the corresponding three-way interaction in Experiment 1, confirming that the difference between the 0- and the 700-msec search slopes was greater in the oddball than in the T/L condition.

The results in Figure 4 reveal a pattern very similar to that obtained in Experiment 1 (Figure 2). This supports the conclusion that the results of Experiment 1—notably, the three-way interaction effect among task, SOA, and number of elements—arose not from intrinsic difference between the SUB and the T/L tasks, but from the different ways in which efficient and inefficient tasks respond to the SOA manipulation. By the same token, the close correspondence of the results in Figures 2 and 4 confirms the predictions from the system reconfiguration hypothesis, as distinct from the resource depletion hypothesis.

GENERAL DISCUSSION

The Theoretical Context

In the present work, we examined two contrasting views regarding the efficiency of visual search under dual-task conditions: the resource depletion and the system reconfiguration hypotheses. In the conventional resource depletion view, the visual system is seen as having a built-in static architecture, with processing advancing through a series of feedforward stages, some of them strictly resource limited. This general model has been used to explain the outcomes of investigations in such areas as visual search (Duncan & Humphreys, 1989; Selfridge, 1959), the attentional blink (Duncan, Ward, & Shapiro, 1994; Jolicoeur, 1999), dual-task interference (Kahneman, 1973), and the psychological refractory period (Pashler, 1998).

An alternative view, espoused in the present work, is that, far from being static, the visual system is dynamically reconfigured from moment to moment so as to be optimally tuned to the expected input. This view is related to theoretical models in which visual information processing is said to be mediated by neural activity along reentrant pathways connecting different brain regions (Di Lollo, Enns, & Rensink, 2000; Di Lollo et al., 2001; Grossberg, 1995; Lee, Mumford, Romero, & Lamme, 1998; Mumford, 1992). On this view, perceptions emerge when the stimulus input is matched to a multidimensional

template stored within the system. The matching process can be performed in one of two ways: by *direct matching* or by *template matching*. Direct matching is fast and yields efficient shallow search slopes under single-task conditions. Template matching is slower and yields inefficient steep search slopes under single-task conditions.

In the direct-matching mode, the system is configured as an input filter tuned to the characteristics of the incoming stimulus. This is tantamount to saying that the appropriate template is embodied in the filter's configuration. If the incoming stimulus fits that configuration, perception occurs directly and immediately, because the stimulus fits the perceptual template embodied in the filter. Direct matching is possible if there has been sufficient time for the system to be suitably configured. It should be noted, at least in passing, that direct matching bears distinct similarities to the process of top-down activation of broadly tuned channels postulated in Wolfe's (1994) Guided Search model.

The template-matching mode, on the other hand, is used when the stimulus is too complex or when there has not been sufficient time for the system to be suitably configured. Unlike direct matching, for which the feedforward sweep alone is sufficient, template matching requires reentrant processing. In reentrant processing, perceptions emerge from iterative exchanges between brain regions linked by reentrant pathways. Upon arriving at higher levels, the feedforward sweep activates a range of perceptual templates representing potential matches for the incoming stimulus. These templates function as perceptual hypotheses that are sent back as reentrant signals to be compared, perhaps through a process of correlation, with the ongoing activity triggered by the incoming stimulus at the lower levels. Conscious perception occurs when the correlation between a template and the incoming stimulus exceeds a criterial level. Because it involves reentrant processing, template matching takes longer than direct matching and yields less efficient, steeper search slopes.

Theoretical Implications of the Present Findings

We now will consider the implications of the present findings for the theoretical views outlined above. There were two main findings. The first involved two tasks that are performed efficiently (i.e., yield shallow search slopes) as single tasks: subitizing and oddball detection. We found that the efficiency of these tasks was impaired (i.e., the slopes became steeper) when they were performed directly after another task, but not when a suitable temporal interval was inserted between the leading and the trailing components of the dual task. These results are inconsistent with the resource depletion model, in which tasks that yield shallow search slopes are said to be performed preattentively and, therefore, without any drain on attentional resources. On this hypothesis, the functions in Figures 2A and 4A should have been shallow and parallel, regardless of SOA.

In contrast, those findings are entirely consistent with the system reconfiguration model. On this view, a task is performed efficiently if it can be done in direct-matching mode.

However, as was noted above, direct matching is possible only when the system can be configured optimally for that task. In the case of the SUB and the oddball tasks, this was possible either under single-task conditions or when a sufficiently long period (SOA) was inserted between the leading and the trailing tasks. A long SOA allowed the system to be suitably reconfigured, and the trailing task could then be performed in direct-matching mode (700-msec curves in Figures 2A and 4A). By the same token, when either the SUB or the oddball task was done directly after the leading task (short SOA), the system was configured optimally for the leading task, causing the trailing task to be carried out in the slower and less efficient template-matching mode (200-msec and 0-msec curves in Figures 2A and 4A, respectively).

The second main result involved a T/L task, known to be performed inefficiently as a single task. We found that this task was performed just as inefficiently under dual-task conditions as under single-task conditions. More important, the T/L search was just as inefficient when performed directly after another task as when a delay was inserted between the two tasks (Figures 2B and 4B). This finding is inconsistent with the resource depletion hypothesis, which predicts a further loss of efficiency when the task is performed directly after another task—namely, while attentional resources are deployed to the leading task. In addition, and contrary to the present findings, the resource depletion hypothesis predicts that efficiency should improve when an interval is inserted between the two tasks. Such an interval would allow the processing of the leading stimulus to be completed and attentional resources to be redeployed to the trailing task.

In contrast, the present findings are consistent with the system reconfiguration model, in which efficiency depends exclusively on whether the system can be configured optimally for that task. Given that the system cannot be configured to perform the T/L task efficiently even as a single task, it follows that this task must be performed using the relatively slow and inefficient template-matching mode, regardless of how long an interval is inserted between the components of the dual-task sequence. On this reasoning, the slope of the search function should remain invariant with SOA, a prediction confirmed by the results shown in Figures 2B and 4B.

Concluding Comments

Two conceptions of visual functioning were juxtaposed in the present work: one based on a static architecture of the visual system, in which preattentive processing is said to be mediated by built-in analyzers, and the other based on a dynamic architecture that can be quickly reconfigured to optimize performance on different tasks at different times. Evidence favoring the dynamic system was reported in earlier dual-task experiments (Di Lollo et al., 2001), but that evidence was limited to the case in which the trailing task could be performed efficiently when done as a single task. The generality of those findings was extended in the present work to the case in which the trailing

task is done inefficiently when done singly, thus enhancing the scope and significance of the earlier findings.

REFERENCES

- DI LOLLO, V., ENNS, J. T., & RENSINK, R. A. (2000). Competition for consciousness among visual events: The psychophysics of reentrant visual processes. *Journal of Experimental Psychology: General*, **129**, 481-507.
- DI LOLLO, V., KAWAHARA, J., ZUVIC, S. M., & VISSER, T. A. W. (2001). The preattentive emperor has no clothes: A dynamic redressing. *Journal of Experimental Psychology: General*, **130**, 479-492.
- DUNCAN, J., & HUMPHREYS, G. (1989). Visual search and stimulus similarity. *Psychological Review*, **96**, 433-458.
- DUNCAN, J., WARD, R., & SHAPIRO, K. L. (1994). Direct measurement of attentional dwell time in human vision. *Nature*, **369**, 313-315.
- GROSSBERG, S. (1995). The attentive brain. *American Scientist*, **83**, 438-449.
- JAMES, W. (1950). *The principles of psychology* (Vol. 1). New York: Dover. [Original work published 1890]
- JIANG, Y., & CHUN, M. M. (2001). Selective attention modulates implicit learning. *Quarterly Journal of Experimental Psychology*, **54**, 1105-1124.
- JOLICŒUR, P. (1999). Concurrent response-selection demands modulate the attentional blink. *Journal of Experimental Psychology: Human Perception & Performance*, **25**, 1097-1113.
- KAHNEMAN, D. (1973). *Attention and effort*. New York: Prentice Hall.
- KAWAHARA, J.-I., ZUVIC, S. M., ENNS, J. T., & DI LOLLO, V. (2003). Task switching mediates the attentional blink even without backward masking. *Perception & Psychophysics*, **65**, 339-351.
- LEE, T. S., MUMFORD, D., ROMERO, R., & LAMME, V. (1998). The role of the primary visual cortex in higher level vision. *Vision Research*, **38**, 2429-2454.
- MONSELL, S. (1996). Control of mental processes. In V. Bruce (Ed.), *Unsolved mysteries of the mind: Tutorial essays in cognition* (pp. 93-148). Hove, UK: Erlbaum.
- MUMFORD, D. (1992). On the computational architecture of the neocortex: II. The role of cortico-cortical loops. *Biological Cybernetics*, **66**, 241-251.
- PASHLER, H. E. (1989). Dissociations and dependencies between speed and accuracy: Evidence for a two-component theory of divided attention in simple tasks. *Cognitive Psychology*, **21**, 469-514.
- PASHLER, H. E. (1998). *The psychology of attention*. Cambridge, MA: MIT Press.
- SAGI, D., & JULESZ, B. (1985). "Where" and "What" in vision. *Science*, **228**, 1217-1219.
- SELFIDGE, O. (1959). Pandemonium: A paradigm for learning. In D. V. Blake & A. M. Uttley (Eds.), *Proceedings of the Symposium on the Mechanization of Thought Processes*. London: HM Stationery Office.
- TAYLOR, M. M., & CREELMAN, C. D. (1967). PEST: Efficient estimates on probability functions. *Journal of the Acoustical Society of America*, **41**, 782-787.
- VISSER, T. A. W., BISCHOF, W. F., & DI LOLLO, V. (1999). Attentional switching in spatial and nonspatial domains: Evidence from the attentional blink. *Psychological Bulletin*, **125**, 458-469.
- WOLFE, J. M. (1994). Guided Search 2.0: A revised model of visual search. *Psychonomic Bulletin & Review*, **1**, 202-238.
- WOLFE, J. M. (1998). What can 1 million trials tell us about visual search? *Psychological Science*, **9**, 33-39.
- WOLFE, J. M., CAVE, K. R., & FRANZEL, S. L. (1989). Guided search: An alternative to the feature-integration model for visual search. *Journal of Experimental Psychology: Human Perception & Performance*, **15**, 419-433.
- WOODMAN, G. F., VOGEL, E. K., & LUCK, S. J. (2001). Visual search remains efficient when visual working memory is full. *Psychological Science*, **12**, 219-224.