Research Article

Effect of Template Complexity on Visual Search and Dual-Task Performance

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ABSTRACT—*Even dissimilar tasks interfere with one another when done together. We used visual search to examine the underlying cause of such interference. In many models, visual search is a process of biased competition controlled by a template describing the target to be sought. When the display is processed, matching against this template guides attention to the target. We show that increasing template complexity increased interference with a dissimilar concurrent task, story memory. This result was independent of reaction time: Increases in template complexity were associated with no increase in search time in Experiment 1 and with a decrease in search time in Experiment 2. The results show that the dual-task demands of visual search reflect the complexity of the template used in task control, and that this factor can be isolated from other sources of difficulty.*

When two tasks are performed together, they are typically done worse than when they are performed alone. This interference is often substantial, especially when the tasks share some common element of processing. For example, Treisman and Davies (1973) and Duncan, Martens, and Ward (1997) showed that interference was greater when two visual tasks were done together or when two auditory tasks were done together than when either visual task was combined with either auditory task. Similar effects have been identified when the shared element is, for example, spatial processing, linguistic coding, or motor response. These *specific* interference effects account successfully for most reports of dual-task interference. In these cases, it is relatively easy to understand why dual-task interference occurs. It occurs because content-specific systems that are limited in their processing ability have to deal simultaneously with separate inputs and outputs. Yet this is not the full story. There are, in addition, tasks that have no obvious specific components in common but that nonetheless interfere with one another when done together (Bourke, 1997; Bourke, Duncan, & Nimmo-Smith, 1996). It is illogical to imagine that interference can occur without two tasks sharing some aspect of processing. What cognitive explanation might exist for such *general* interference?

One possible explanation emerges from the neurologically plausible *global workspace* concept of Dehaene and his colleagues (Dehaene, Kerszberg, & Changeux, 1998; Dehaene, Sergent, & Changeux, 2003). In their computational model, every task has multiple hierarchically organized levels of competition. At low levels, competition is within functionally specialized processors (e.g., perceptual, memory, and motor processors). At high levels, competition is within a global workspace. Global workspace is characterized by a network of dispersed but heavily interconnected neurons that can be accessed by the specialized processors. Only a subset of inputs from the specialized processors can effectively access the workspace at a time. But what makes strong demands on such global workspace, thus attenuating other inputs and leading to poor dual-task performance?

We examined this question using a dual-task paradigm in which we manipulated different sources of difficulty in a visual search task. In visual search, people have to decide if any element in a display matches a predefined target. A number of demands can be manipulated independently in this task. First, task demands depend on the specification of the target currently being sought. Models commonly propose an internal template describing this target (e.g., Desimone & Duncan, 1995). When

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the display is processed, matching against this template guides attention to the target (Bundesen, 1990; Cave & Wolfe, 1990; Duncan & Humphreys, 1989). Task difficulty might be increased by increasing the complexity of the target. For example, if the visual task is to decide if a red *O* is present in an array of green *O*s, then a relatively simple template, specifying just target color, might be established. In contrast, in a classic conjunction task, the decision is whether a red *O* is present among green *O*s and red *X*s. In this case, the definition of the target depends on both shape and color. Second, difficulty of a visual search task can be manipulated through variables affecting the visual display itself, such as stimulus contrast or the number of elements presented.

In Experiment 1, we contrasted effects of template complexity and number of items in the display. The results show that display size is a crucial factor in task difficulty, as reflected in reaction time, but template complexity determines dual-task interference. In Experiment 2, we investigated the dual-task effects of an increase in template complexity in the context of a manipulation that decreased reaction time. Together, the results show that dual-task interference is not predicted by simple task difficulty, as reflected in reaction time. The key factor, instead, is the complexity of the target template—the rule specifying how the task should be performed.

EXPERIMENT 1

In this experiment, participants performed a memory task either alone or concurrently with one of three visual search tasks. The first visual task was designed to vary from the second in having a lower level of template complexity but to be equal to the second task in reaction time. The third task was designed to be equal to the second task in template complexity but to show an increase in reaction time owing to increased set size.

Method

Participants

Sixty-four participants were tested, 16 in each of four conditions. Participants were first- and second-year undergraduate psychology students, predominantly female, with a modal age of 19. They participated for participant-pool credit, a voluntary system that allows subsequent use of the pool. They were not informed of the purpose of the experiment and were unfamiliar with the story that was played for the memory task, as well as with the visual search tasks used.

Procedure

In each of the three visual search tasks, the participant had to decide if the letter *L* was present. This target was present on 50% of the trials. The target could occur at one of eight positions evenly spaced on the perimeter of an imaginary circle that was centered on a fixation cross and had a radius of approximately 5.4°. In the first task, participants had to decide if a target letter *L* was present in a display that could consist of eight *O*s or seven *O*s and an *L*. Conventionally, this is considered a *feature search* task, because any of several single features (e.g., curvature, closure) can be used to distinguish targets from distractors. In the second task, only a single *L* was presented on each trial, and participants had to decide whether the letter was the target, an *L* in its correct orientation, or a distractor, an *L* that had been rotated 90° to the left or to the right. Conventionally, this is considered a *conjunction* task because the target can be defined only by the correct combination of its component strokes (e.g., Wolfe, Cave, & Franzel, 1989). Accordingly, we assumed the template for this task would be more complex than the template for the first task. The third task was a *conjunction-with-distractors* task. The same target was used as for the second task, but when present, it was among a display of seven other *L*-shaped characters, which were pseudorandomly rotated to the left or right by 90°. When the target was not present, the display consisted of eight rotated *L*s. This third task followed Experiment 3 in Duncan and Humphreys (1989).

On all three tasks, participants responded by pressing one of two keys on a standard keyboard. To indicate that the target was present, they pressed a key on the left that was marked "yes," and to indicate that the target was absent, they pressed a key on the right that was marked "no." Each response initiated the next trial immediately.

After pilot testing, story memory was chosen as a suitable concurrent task, because it fulfilled the criterion of avoiding specific sources of interference. The story used was a 3-min extract from a talking book (Singh, 1997). Participants heard the segment under either dual-task or single-task conditions and were asked to recall the story under single-task conditions.

Participants were randomly allocated to one of four groups. In the first, the single-task condition, participants simply listened to the story extract and recalled it when the presentation ended. The other three groups performed one of the three visual search tasks described earlier. Each participant did his or her allocated visual search both alone and under dual-task conditions. The order was counterbalanced within groups. For the dual-task testing, participants were told that in addition to doing the visual task, they should listen to a tape of a part of a story that would be played at the same time. They were also told that at the end of 3 min, they would be asked to recall as much as they could about the story—the gist, names, or any details—but that they should consider the visual task the main task and work as fast and accurately as they could on that. Requiring an immediate response in visual search but not in story memory facilitated this instruction. At the end of 3 min, the tape was stopped, and the participants were asked to recall as much as they could of what they had heard. Participants were prompted once by being asked, "Anything else?" when they stopped talking, and the recall session concluded 10 s after recall ceased. Recall was audiotaped and transcribed.

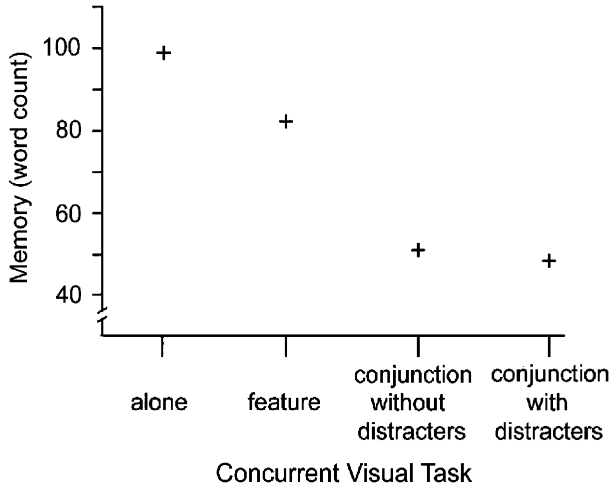

Fig. 1. Story memory (number of words recalled) in Experiment 1 when this task was performed alone or concurrently with feature search, conjunction search without distractors, or conjunction search with distractors.

The transcripts were scored in two ways: word count and number of idea units recalled. For word count, the transcripts were edited to remove only self-commentary (e.g., "I can't remember any more") and verbal hesitations (e.g., "umm"). Then an automated word count was done on each transcript. Six scorers used a written version of the story passage to agree upon the idea units in it and then practiced scoring 15 sample transcripts obtained from pilot work on the same passage. Scoring discrepancies were noted for each transcript, and the scorers agreed on how to score such items in the future. Agreement among the scorers was high from the beginning, with the average deviation being 0.64 (range from 0 to 1.16). The transcripts from the four conditions were shuffled and then marked blind by the same six independent markers.

Results

Overall, memory performance showed a significant difference across the four conditions, Kruskal-Wallis $H = 16.19$, $N = 64$, $p < .001$, $\eta_p^2 = .257$. This effect is shown in Figure 1. Recall scores were worse when the memory task was concurrent with the conjunction-without-distractors task than when it was concurrent with the feature search task, $U = 81$, $n = 32$, $p = .040$ (one-tailed), $\eta_p^2 = .101$. Clearly, there was no difference in recall when the story memory task was concurrent with the conjunction-without-distractors task and when it was concurrent with the conjunction-with-distractors task, $U = 112$, $n = 32$, $p = .54$.

The same pattern of significant differences across the conditions was obtained for number of idea units recalled, $H = 30.13$, $N = 64$, $p < .001$, $\eta_p^2 = .478$. Thirty-six ideas were identified. Under single-task conditions, a mean of 9.5 ideas were recalled. A one-tailed Mann-Whitney U test showed a significant difference between the feature search condition ($M = 6$) and the conjunction-without-distractors condition ($M = 4.9$), $U = 83$, $n = 32$, $p = .047$, $\eta_p^2 = .093$. The difference between the conjunction-without-distractors condition and the conjunction-with-distractors condition ($M = 5.1$) was not significant, $U = 128$, $n = 32$, $p = .5$.

The reaction time results in the three visual search conditions (Fig. 2) show a contrasting pattern. There was a main effect of visual search condition, $F(2, 42) = 112.87$, $p < .001$, $\eta_p^2 = .84$. This effect was clearly due to the difference between the conjunction-with-distractors condition and the other two conditions. In addition, there was a significant increase in reaction time in the dual-task compared with the single-task condition, $F(1, 42) = 64.88$, $p < .001$, $\eta_p^2 = .61$, as well as an interaction between single-task/dual-task condition and visual search condition, $F(2, 42) = 55.39$, $p < .001$, $\eta_p^2 = .73$. Reaction times were shorter overall for target-present than for target-absent trials, $F(1, 42) = 10.21$, $p = .003$, $\eta_p^2 = .20$. The effect of target presence/absence also interacted with visual search condition, $F(2, 42) = 8.44$, $p = .001$, $\eta_p^2 = .29$.

Error rates are shown in Table 1. There was a significant effect of visual search condition, $F(2, 42) = 64.78$, $p < .001$, $\eta_p^2 = .76$, largely due to high error rates in the conjunction-with-distractors condition.

Discussion

The most striking aspect of the results is that the effect of the manipulations on reaction time was not reflected in the effects on dual-task performance. First, feature search and conjunc-

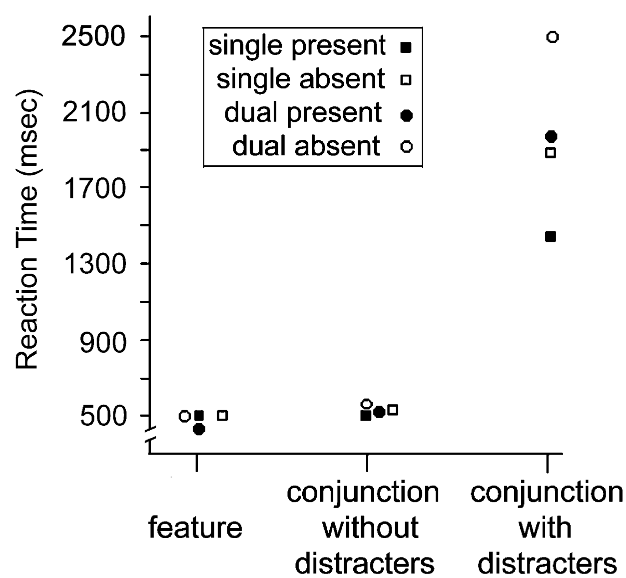

Fig. 2. Visual search times for the three visual search tasks (feature search, conjunction search without distractors, and conjunction search with distractors) in Experiment 1. Results are shown separately for target-present and target-absent trials in the single- and dual-task conditions.

TABLE 1
Experiment 1: Proportion of Errors on the Visual Search Tasks Under Single- and Dual-Task Conditions

	Search task		
Condition	Feature	Conjunction without distractors	Conjunction with distractors
Single-task	.0086	.0219	.0819
Dual-task	.0110	.0269	.1060

tion-without-distractors search did not differ in reaction times (or number of trials presented), but there was a significant decrement in dual-task performance for conjunction-without-distractors search relative to feature search. Second, reaction times were significantly longer for conjunction-with-distractors search than for conjunction-without-distractors search, but dual-task performance did not differ between these two conditions. Thus, dual-task performance cannot be predicted from reaction time.

The pattern in dual-task performance was consistent with our expectations. Only the simplest template needs to be used to perform a feature search task. In contrast, by hypothesis, a detailed template is needed to specify the exact combination of strokes defining an upright *L*. Thus, if the complexity of the template in a visual search is the critical element in predicting performance on a concurrent task, one would expect worse performance on the second task when it is done concurrently with conjunction search rather than feature search. Indeed, in the current experiment, dual-task performance was worse in the conjunction search conditions than in the feature search condition. However, the template for the conjunction-with-distractors condition (in which eight *L*s were presented) required the same level of specification as in the template for the conjunction-without-distractors condition, so these two conditions did not lead to different levels of dual-task interference.

It was possible that a floor effect was the reason why the two conjunction search conditions showed no difference in performance on the memory task. To test this possibility, we varied template complexity over more than two levels in Experiment 2.

EXPERIMENT 2

In this experiment, we explicitly opposed template complexity and reaction time. Three conditions were studied. In the first condition, visual search could be done on the basis of a single feature (color or form). In the second condition, the search required using two features (color and form). In the third condition, the search had to use three features (color, form, and size). We assumed that as the number of features defining the target increased, there would be a corresponding increase in template complexity. A decrease in performance of the concurrent task was expected to accompany this increase in template complexity. However, Wolfe et al. (1989) showed that reaction times are faster in a triple-conjunction task than in the classic double-conjunction task (providing each distractor shares only one feature with the target), so we expected reaction times to decrease as template complexity increased from the double to the triple conjunction.

Method

Participants
Forty-eight participants were tested, 16 in each of three conditions. Participants were first-year psychology undergraduates, predominantly female, with a modal age of 18. They were naive to the purpose of the experiment and had not participated in previous visual search experiments. They participated for participant-pool credit.

Procedure
The story memory task was the same as that described in Experiment 1 and was run in the same way (except that there was no single-task condition for this task). The visual search tasks were run on an IBM-compatible computer and presented on a 17-in. monitor with a standard screen resolution. There were three types of visual search task: a feature search, a double-conjunction search, and a triple-conjunction search. The latter two tasks followed the descriptions of Wolfe et al. (1989). Participants in each of the three conditions performed one of these visual search tasks for 3 min both with and without the concurrent story memory task, with order of the single-task and dual-task parts of the experiment counterbalanced.

For each visual search task, on any given trial, 8, 16, or 32 stimuli were presented at randomly picked positions in a 6×6 array (600 pixels $\times$ 600 pixels). Stimuli were centered around these positions, randomly jittered by ± 30 pixels. The array was approximately $11^\circ \times 11^\circ$ and was viewed from a distance of 1 m. The stimuli were the letters *X* and *O* drawn to fill an imaginary area approximately $0.85^\circ \times 0.85^\circ$. In addition, in the triple-conjunction condition, some of the letters were half this size. A (2-pixel) white fixation dot at the center of the display was present throughout the experiment. Two colors were used, a fully saturated red that measured 255 on the 24-bit color-depth scale and a green that measured 191 on the same scale. Stimuli were presented on a black background. In all three visual search conditions, the target was a red *O* that appeared on 50% of the trials. In feature search, it appeared among green *X*s. In the double-conjunction search, the target appeared among red *X*s and green *O*s. In the triple-conjunction search, it appeared among green *X*s, small red *X*s, and small green *O*s. Types of distractor items always occurred with equal probability.

On each trial, participants had to decide if the target was present or not. They had to do this as rapidly as possible while avoiding errors, again regarding this task as primary in dual-task conditions. Participants responded by pressing the "yes" (right side) or "no" (left side) key of a two-button response box. After each response, the screen went blank, and a 1-s feedback display appeared. Feedback consisted of information on both accuracy ("correct" or "incorrect," 32 pixels above the fixation point) and reaction time (just under the fixation point). Immediately after the feedback, the next trial was presented. Participants worked through the trials until interrupted by the experimenter. Set size randomly varied among 8, 16, and 32 items. Prior to testing, the participants were familiarized with the button box by performing 40 practice trials searching for a magenta square among green *O*s.

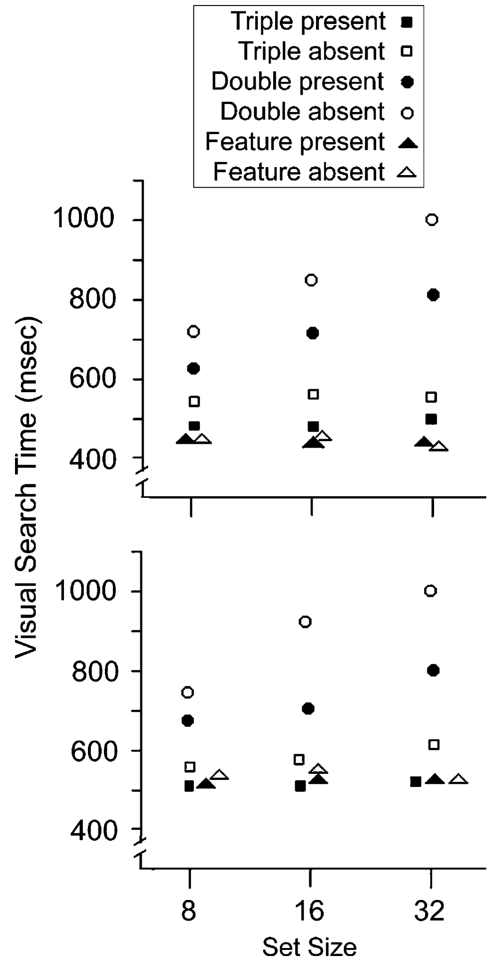

Fig. 4. Visual search times for set sizes of 8, 16, and 32 in the single-task (top) and dual-task (bottom) conditions of Experiment 2. Results are shown separately for target-present and target-absent trials in each of the three visual search tasks (feature search, double-conjunction search, and triple-conjunction search).

Results

Figure 3 shows mean word count on the story task when it was done concurrently with each of the three visual search tasks. Single-task memory performance from Experiment 1 is included for reference. For the dual-task conditions, a Jonckheere-Terpstra (J) trend test showed a monotonic decrease in recall as the supposed template complexity increased, $J = 265$, $N = 48$, $p = .012$ (one-tailed), $\eta_p^2 = .091$. One marker scored the transcripts using the idea-units method. These scores produced no significant difference between conditions, $J = 366.5$, $N = 48$, $p = .77$.

The reaction time results, shown in Figure 4, contrast with the pattern in the memory scores. The key comparison of interest is between the double- and the triple-conjunction conditions. An analysis of variance including just these two conditions showed a main effect of condition, $F(1, 30) = 20.11$, $p < .001$, $\eta_p^2 = .40$. There was also a main effect of set size, $F(2, 60) = 54.9$, $p < .001$, $\eta_p^2 = .65$. Set size interacted with condition, $F(2, 60) = 31.99$, $p < .001$, $\eta_p^2 = .52$. There was no effect of the dual-task factor, nor did it interact with any other factor. There was a main effect of target presence/absence, $F(1, 30) = 56.29$, $p < .001$, $\eta_p^2 = .65$, which interacted with condition, $F(1, 30) = 8.10$, $p = .008$, $\eta_p^2 = .213$, and set size, $F(2, 60) = 5.13$, $p = .009$, $\eta_p^2 = .15$. Mean reaction times were better in the triple-conjunction task ($M = 538$ ms) than in the double-conjunction task ($M = 802$ ms). In contrast, memory (word count) for the story was worse in the triple-conjunction task (54 words) than in the double-conjunction task (78 words). The decrease in memory was significant, $U = 67$, $n = 32$, $p = .021$ (one-tailed), $\eta_p^2 = .171$. Error rates for all three search tasks are presented in Table 2.

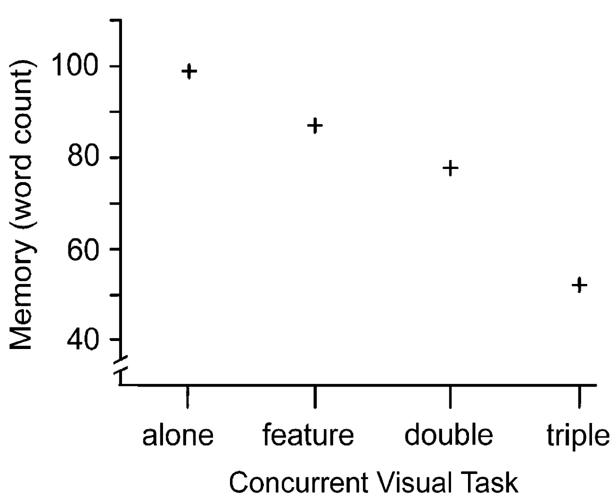

Fig. 3. Story memory (number of words recalled) when this task was done alone (Experiment 1) or concurrently with feature search, double-conjunction search, or triple-conjunction search (Experiment 2).

Discussion

The degree to which the three visual search tasks interfered with memory (word count) for the story did not reflect their

TABLE 2
Experiment 2: Proportion of Errors on the Visual Search Tasks Under Single- and Dual-Task Conditions

	Search task		
Condition	Feature	Double conjunction	Triple conjunction
Single-task	.0153	.0187	.0159
Dual-task	.0143	.0206	.0133

relative difficulty as measured by reaction times. Memory was best when the primary task was the feature search, worse when it was the double-conjunction search, and worst when it was the triple-conjunction search. The reason for the lack of variation in recall as measured by idea units is unclear; perhaps idea units are a less sensitive measure of memory than word count is. In contrast to recall, reaction times were very much better (i.e., shorter) for triple than double conjunctions. Because of the opposing results for memory and reaction time, explanations based on floor, ceiling, and plateau effects can be ruled out.

GENERAL DISCUSSION

Across the experiments, the results consistently showed dissociations between how changes in the visual tasks affected reaction times and dual-task performance. It seems that reaction time and dual-task performance reflect different factors in the visual search process.

What is the basis for conflict between story memory and a visual search template? If participants engage in explicit verbal rehearsal of the search template, this might produce strong interference with a concurrent verbal (story) task. In the case of Experiment 2, it might be conceivable that verbal rehearsal was more common for triple than for double conjunctions. This seems an unattractive explanation, however, for the results in Experiment 1, in which the target was always just the upright letter *L*.

The global neuronal workspace model introduced earlier (Dehaene et al., 2003) offers a better explanation of the results. Useful though it is, this broad model needs to be developed by specifying which factors are important in workspace demand. The current experiments are a step in this direction. They show that—at least in visual search—workspace demand is not predicted by the complexity of display processing, as reflected in search reaction time. Instead the key factor is complexity of the target template. In visual search, the template may be seen as a top-down control signal determining current task requirements. More generally, a central role of the global workspace may be to code current task rules that control how inputs are processed and decisions are made.

Of course, much more research is needed to establish the role of a global workspace in different tasks. Our data imply that it has some important role, for example, in text comprehension and memory, but they do not address what that role might be. Already, however, they suggest that workspace demand cannot be predicted by simple task difficulty. As illustrated by our search results, some forms of difficulty are more important than others.

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