Load Theory of Selective Attention and Cognitive Control

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Load Theory of Selective Attention and Cognitive Control

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A load theory of attention in which distractor rejection depends on the level and type of load involved in current processing was tested. A series of experiments demonstrates that whereas high perceptual load reduces distractor interference, working memory load or dual-task coordination load increases distractor interference. These findings suggest 2 selective attention mechanisms: a perceptual selection mechanism serving to reduce distractor perception in situations of high perceptual load that exhaust perceptual capacity in processing relevant stimuli and a cognitive control mechanism that reduces interference from perceived distractors as long as cognitive control functions are available to maintain current priorities (low cognitive load). This theory resolves the long-standing early versus late selection debate and clarifies the role of cognitive control in selective attention.

Goal-directed behavior requires focusing attention on goal-relevant stimuli while ignoring irrelevant distractors. However, the mechanisms for such behavioral control by selective attention remain to be elucidated. In this article, we present a load theory of attention that proposes two mechanisms of selective attention. The first is a perceptual selection mechanism that allows for excluding irrelevant distractor stimuli from perception under situations of high perceptual load (see Lavie, 1995; Lavie & Tsal, 1994). This is a rather passive mechanism, whereby irrelevant distractor interference is prevented simply because the distractors are not perceived when there is insufficient capacity for their processing. The second mechanism is a more active mechanism of attentional control that is needed for rejecting irrelevant distractors even when these are perceived (in situations of low perceptual load). This form of control depends on higher cognitive functions, such as working memory, that are required for actively maintaining current processing priorities to ensure that low-priority stimuli do not gain control of behavior. Thus, contrary to the predicted effect for perceptual load, high load on these cognitive functions should drain the capacity available for active control and result in increased processing of irrelevant distractors.

These two types of mechanism for selective attention can thus be dissociated through the opposite effects different types of load should have on interference from irrelevant distractors. Whereas increasing perceptual load is expected to reduce distractor interference, increasing cognitive control load is expected to increase distractor interference. We begin by reviewing the existing evidence for this theory and then proceed to describe a series of new studies that provide support for our proposed distinction between the two mechanisms of selective attention.

Effects of Perceptual Load on Distractor Perception

The extent to which perception of irrelevant distractors can ever be prevented has been debated for the last 4 decades of attention research between those who hold early selection views that suggest that focused attention can effectively prevent early perceptual processing of irrelevant distractors (e.g., Treisman, 1969) and those who hold late selection views that suggest that attention can only affect later postperceptual processes such as memory or response selection (e.g., Duncan, 1980). The debate between those with early and late selection views on the extent to which irrelevant stimuli are perceived stimulated much psychological research in the last few decades. A resolution proved very elusive, however, because substantial evidence supports both points of view. Many of the early studies of attention that used the dichotic listening paradigm in hearing and the selective looking paradigm in vision demonstrated that unattended information typically goes unnoticed (e.g., Neisser & Becklen, 1975; Rock & Gutman, 1981; Treisman & Geffen, 1967), a result that supports the early selection view. However, the late selection view received support in many subsequent studies that used indirect measures of distractor perception in Stroop-like tasks (e.g., the flanker task; Eriksen & Eriksen, 1974). Target responses in these studies were often slower in the presence of an irrelevant distractor whose identity was associated with an incongruent response (vs. a congruent response or no response), thus indicating that the distractor identity was perceived and its association with response recognized. Such results were found even when the distractors were clearly separated from the

target (appearing in some instances as far as 5° away from the target; Gatti & Egeth, 1978). It might be tempting to conclude that differences in the paradigms that lent support for either view are responsible for the different results. For example, one might claim that the indirect measures that supported late selection in Stroop-like tasks are better able to reveal unattended perception than are the explicit reports that supported early selection in the dichotic listening and selective looking experiments. However, support for the early selection view was also obtained in Stroop-like tasks. In fact, under some circumstances (e.g., with effective cuing of attention to targets and with more cluttered displays; see Kahneman & Chajczyk, 1983; Yantis & Johnston, 1990; see also more recent demonstrations in Brown, Gore, & Carr, 2002; Jenkins, Lavie, & Driver, 2003), distractor perception has been reduced or diluted (thus supporting early selection views) in studies using Stroop-like tasks very similar to those that have previously provided ample support for the late selection view. The existence of discrepant evidence even within the same task has led some to doubt that the early and late selection debate can ever be resolved (e.g., Allport, 1993).

However, Lavie (1995, 2001; Lavie & Tsal, 1994) has recently suggested that a resolution to the early and late selection debate may be found if a hybrid model of attention that combines aspects from both views is considered. According to this model, distractors can be excluded from perception when the level of perceptual load in processing task-relevant stimuli is sufficiently high to exhaust perceptual capacity, leaving none of this capacity available for distractor processing. However, in situations of low perceptual load, any spare capacity left over from the less demanding relevant processing will spill over to the processing of irrelevant distractors. Thus, in this model, early selection is predicted for situations of high perceptual load, whereas late selection is predicted for situations of low perceptual load. A review of the previous selective attention studies provided support for this model (Lavie & Tsal, 1994). The experimental situations in the studies that provided support for late selection clearly involved a low level of perceptual load (often with just one target and one distractor identity present; e.g., see Gatti & Egeth, 1978), whereas the experimental situations in the studies that provided support for early selection could be generally characterized as carrying a higher level of load (e.g., with a greater number of stimuli present in the studies of Kahneman & Chajczyk, 1983; Yantis & Johnston, 1990).

The previous studies did not include a direct manipulation of load on target perception, and the dilution of distractor effects in more cluttered arrays could be attributed to factors other than reduction in the available capacity for distractor processing (e.g., reduced saliency of the critical response-related distractor in the presence of other distractor stimuli). In a series of new studies, Lavie and her colleagues directly manipulated the level of perceptual load in target processing and measured the effects on irrelevant distractor processing. The concept of perceptual load implies either that more items are added for the same task or that for the same number of items, a more demanding perceptual task is carried out under higher perceptual load. It is these items or operations that consume attentional capacity in the relevant processing and thereby block irrelevant processing.[1] In line with this claim, Lavie (1995; Lavie & Cox, 1997) demonstrated that increasing the number of items that are relevant for target perception or increasing the perceptual processing requirements for the same

items (e.g., comparing simple presence detection vs. complex discrimination of feature conjunctions) leads to reduced interference effects from irrelevant distractors in flanker tasks.

Further studies provided support for the claim made by the perceptual load model that the reduction in distractor interference found under higher perceptual load indicates that perception becomes more selective under high perceptual load. Lavie and Fox (2000) showed that perceptual load reduces not only distractor interference effects on concurrent target reaction times (RTs) but also any subsequent effects of negative priming (NP; i.e., the slowing of responses to previous distractor stimuli when these are presented as the targets on a subsequent trial; e.g., Tipper, 1985). NP effects were found from distractors that were presented in displays of low perceptual load but were eliminated by higher perceptual load in the target processing. As NP is thought to be, to some extent, an index of active distractor inhibition (however, for alternative accounts, see Neill & Valdes, 1992), these studies demonstrate that the reduction in distractor interference seen under high perceptual load is unlikely to be due to increased distractor inhibition but is rather more likely to be the result of reduced distractor perception. A different line of evidence for the claim that distractor perception is reduced in high perceptual load was obtained in a neuroimaging study that showed that neural activity in visual cortices associated with the perception of irrelevant motion distractors (e.g., area MT/V5) was reduced under higher load in a relevant yet unrelated task of linguistic judgments performed on words presented at fixation (Rees, Frith, & Lavie, 1997).

In summary, several studies of perceptual load converged to show that distractor processing is reduced in conditions of high perceptual load. These studies used various manipulations of perceptual load as well as various measures for distractor processing and thus provide strong convergent evidence for the claim that attention can prevent distractor perception (producing early selection effects) under situations of high perceptual load when the relevant task exhausts perceptual capacity.

These studies also made it clear that late selection typically occurs in situations of low perceptual load. In the low perceptual load conditions of these studies, the irrelevant distractors were perceived, as demonstrated by the significant interference and NP effects they produced on target RTs in the behavioral experiments as well as by distractor-related activity in Rees et al.'s (1997) neuroimaging experiment. These findings demonstrate that perceptual load is a critical determinant of whether irrelevant distractors are perceived (late selection) or not (early selection) and thus provide a resolution of the early and late selection debate within a hybrid perceptual load model.

Effects of Cognitive Control on Distractor Processing

Perceptual load studies advance the understanding of the circumstances under which distractor perception can be prevented.

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[1] The definition of perceptual load also involves defining what constitutes an item in a display; for example, a string of letters can be considered one item (a word) or several items (letters) in different tasks. Therefore, it is important to compare the number of items within the same task (see Lavie & Tsal, 1994, for a more detailed discussion; see also Lavie & De Fockert, 2003, for boundary conditions for what constitutes an increase in demand on perceptual tasks).

However, a full model for selective attention requires also an account for control of behavior in situations of low perceptual load whereby irrelevant distractors are perceived and so can compete to control behavior. Despite perceiving irrelevant distractors, normal young adults are typically still capable of selecting the correct target response. The ability to ensure such accurate response selection in situations of late selection in which both relevant and irrelevant stimuli are perceived must depend on some active control process that ensures that behavior is appropriately controlled by goal-relevant stimuli rather than goal-irrelevant stimuli. In the following section, we review studies that show that efficient selective attention under low perceptual load requires active cognitive control mechanisms that are dissociable from the more passive early selection mechanism (under high perceptual load) that we have described so far.

A recent study by Maylor and Lavie (1998) provides some support for this dissociation between early and late selection mechanisms. Maylor and Lavie compared the effects of perceptual load on distractor processing between young and old subjects. They found that lower levels of perceptual load were needed to reduce distractor interference in older subjects as compared with a young group. This result was predicted from the perceptual load model (Lavie, 1995) combined with the assumption that aging results in reduced capacity for perception (e.g., Ball, Beard, Roenker, Miller, & Griggs, 1988) so that lower levels of load are already sufficient to exhaust capacity in relevant target processing in the older group. However, the older subjects also suffered from far greater distractor interference effects at very low levels of perceptual load (e.g., when just one target and one distractor were presented). This study thus highlights two components involved in age-related changes in attention. The first is a decreased capacity for perception, which can actually lead to some counterintuitive improvement in mechanisms of early perceptual selection, resulting in reduced processing of distractors in older people as a natural consequence of perceptual capacity being more readily exhausted by relevant processing. The second is an additional age-related decline in those late selection mechanisms that prevent responses to irrelevant distractors that have been perceived in situations of very low perceptual load.

The importance of such active mechanisms of attentional control can also be seen from the various slips of action that can occur if irrelevant response tendencies are not suppressed. Although such failures of attention are relatively infrequent in young healthy adults, there are numerous reports of failures to inhibit irrelevant response tendencies in older adults (e.g., Hasher & Zacks, 1988); these arise in extreme form in patients with frontal-lobe damage (e.g., Shallice & Burgess, 1991). Indeed, the greater distraction found at low perceptual loads in the older subject group of Maylor and Lavie's (1998) study might conceivably be explained by a deterioration of the frontal lobes with aging. Although aging involves a loss of cells in both posterior and anterior cortices, the greatest proportion of cell loss with aging is in the frontal cortex (e.g., Kramer, Humphrey, Larish, Logan, & Strayer, 1994).

Moreover, frontal cortices are known to be involved in various cognitive control processes, such as working memory (Courtney, Ungerleider, Keil, & Haxby, 1997; D'Esposito & Postle, 2000; Goldman-Rakic & Friedman, 1991) and the control of dual-task coordination (D'Esposito et al., 1995; Shallice & Burgess, 1996). These frontal processes of cognitive control seem crucial for maintaining task-processing priorities between relevant and irrelevant stimuli in order to guide behavior in accordance with current goals. We thus propose that when these frontal processes of cognitive control are loaded during performance of a selective attention task, performance will suffer from greater interference by goal-irrelevant distractors.

Notice that we now predict the opposite effect to that found for perceptual load: Higher load in cognitive control functions that serve to actively maintain processing priorities (e.g., working memory) should increase distractor processing rather than decrease distractor processing. Thus, the two functions of attention, namely, selective perception and active control of response selection, can be distinguished from one another by contrasting the effects of different types of load on distractibility. Increases in perceptual load should decrease distraction by engaging perceptual capacity in processing relevant stimuli. By contrast, increases in load on higher level cognitive control functions should increase distraction, as the reduced availability of these control mechanisms for attention would reduce the ability to control attention in accordance with current processing priorities and thus increase intrusions of irrelevant distractors.

In the experiments conducted here, we first focused on the effects of working memory load on the processing of irrelevant visual distractors and then also addressed the effects of cognitive control of dual-task coordination on such distractor processing. Previous work on the role of working memory in attention is reviewed below. As for previous studies of dual-task coordination, these established a general performance cost for coordinating two tasks rather than one in the dual-task paradigm (e.g., Bourke, Duncan, & Nimmo-Smith, 1996) and for switching (vs. no-switching) tasks in the task-switching paradigm (Monsell, 2003). However, it is often hard to isolate the component of cost just due to the higher level cognitive control processes involved in dual-task coordination (e.g., Meiran, 1996; Pashler, 1993) rather than to the need to share (in the dual-task paradigm) or reconfigure (in the task-switching paradigm) specific processes that are involved in the tasks that have to be coordinated. In any case, to the best of our knowledge, there have been no previous studies on the specific effects of dual-task coordination on the efficiency of distractor rejection in selective attention tasks in either paradigm. Below we review the few studies that have addressed the effects of working memory on selective attention.[2]

Previous Studies on the Role of Working Memory Load in Selective Attention

In a series of studies on the role of working memory in visual search, Logan (1978) failed to find any effect of working memory load on the slopes of search set size functions. As the slope of search set size functions reflects the efficiency with which atten-

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[2] We restrict our review to studies that examined the effects of working memory load in tasks of selective attention, characterized by the requirement to ignore irrelevant stimuli, as only these are relevant for our current interest in the role of working memory in maintaining priorities between relevant and irrelevant stimuli. Studies that examined the effects of working memory load on other types of tasks (e.g., signal detection, Kahneman, Beatty, & Pollack, 1967; and spatial discrimination, Egeth, 1977) are beyond the scope of this review.

tion can scan items in the search array, these findings show that the efficiency of attentional search is not affected by working memory load. Logan (1978) used verbal material in the working memory task. More recently, Woodman, Vogel, and Luck (2001) used a visual working memory task and also failed to find any effect of working memory load on the efficiency of visual search performance.

The failure to find any effects of working memory load on search efficiency initially appears to be in direct contrast with the suggestion that working memory serves to maintain the target template for visual search (Duncan & Humphreys, 1989) and also (although somewhat more indirectly) with our current suggestion that working memory serves to maintain current priorities between targets and distractors in selective attention tasks. However, in a recent study, Lavie and De Fockert (2004) manipulated working memory load during visual search and found that working memory load specifically affects *attentional capture* by a salient, although irrelevant, singleton distractor in visual search. Interference in the search for a predefined shape target due to the presence (vs. absence) of an irrelevant color singleton (i.e., attentional capture) was greater in conditions of high (vs. low) working memory load. The contrast between Lavie and De Fockert's results and the previous failures to find effects of working memory load on the efficiency of visual search performance may therefore suggest that cognitive control of visual search by working memory is only needed in competitive situations in which high-priority targets have to compete for attention with low-priority but salient distractors, as we presently suggest.

Further evidence for the involvement of working memory in tasks that involve competing attention-capturing stimuli that need to be suppressed has been obtained in the antisaccade paradigm. Roberts, Hager, and Heron (1994) found that the rate of erroneous reflexive saccades toward a salient cue instead of away from it (as required in the antisaccade paradigm) was increased under conditions of high working memory load (vs. no load). More recently, Kane, Bleckley, Conway, and Engle (2001) reported a correlation between individual differences in working memory span and the rate of erroneous saccades in this task. These findings are in line with our hypothesis on the role of working memory in selective attention. However, although the ability to suppress reflexive saccades to a salient cue should depend to some extent on selective attention, the numerous differences between the antisaccade task and typical selective attention tasks (e.g., in terms of both the stimuli and responses typically used: reflexive eye movements to brief flashes of lights in the antisaccade task vs. nonreflexive manual or verbal responses that are mapped to letters, shapes, or words presented as irrelevant distractors in selective attention tasks) preclude direct inferences. Moreover, our hypothesis specifically focuses on the involvement of working memory in the ability to reject irrelevant distractors, but the cues in antisaccade tasks are task relevant because they indicate the (opposite) direction of saccade.

Evidence for the involvement of working memory in more traditional selective attention tasks was obtained in a recent series of studies that showed that individual differences in working memory span correlate with performance in selective attention tasks. Conway, Cowan, and Bunting (2001) found that a greater number of low-span subjects (65%) detected their name in an unattended channel (i.e., showed the cocktail party effect) than did high-span subjects (20%), thus suggesting that that high-span subjects may be better able to focus attention on the relevant channel of information. Kane and Engle (2003) showed that low-span subjects make more errors of responding to a distracting (low probability; see Logan, 1980) incongruent word in the Stroop task than do high-span subjects, again suggesting that high-span subjects may be better able to ignore irrelevant yet salient distractors. However, because results from correlative studies cannot inform about any causal role, it is not clear from these studies whether working memory plays a causal role in selective attention as we claim or whether the better ability to focus attention allows for better performance in working memory tasks. Moreover, not all measures of working memory span show correlations with performance in selective attention tasks. Measures of span that show such correlations (e.g., the operation-span task; Turner & Engle, 1989) seem to heavily involve an attentional component. For example, in the operation-span task, subjects have to maintain information in working memory (e.g., words) while intermittently performing another (arithmetic) task. This task thus seems to load on both attention-dividing (between the two tasks) and task-switching abilities. The correlations with performance in other selective attention tasks (e.g., Stroop) may therefore be driven from the attentional components in such measures of span.

A different line of evidence for the claim that working memory serves to maintain the distinction between relevant and irrelevant stimuli in selective attention tasks has come from recent electrophysiological studies that found that neurons in prefrontal regions typically associated with working memory were selectively active in accordance with stimulus relevance for attention (Miller, Erickson, & Desimone, 1996; Rainer, Asaad, & Miller, 1998). Moreover, these neurons showed such selective responses in the interval before the onset of the attentional task so as to suggest that they play a role in maintaining an attentional template in working memory.

Finally, the first direct evidence in humans for the causal role we propose for working memory in selective attention was recently provided in a study that combined neuroimaging and behavioral experiments. De Fockert, Rees, Frith, and Lavie (2001) varied working memory load in a "successor-naming" task (requiring memory for digit order) that subjects conducted while performing a selective attention task that required them to classify written famous names and to ignore irrelevant distractor faces. Greater interference on RTs was observed from incongruent distractors (e.g., Bill Clinton's face with Mick Jagger's name) versus neutral or congruent distractors under high (vs. low) working memory load. Moreover, the neuroimaging results showed that visual cortex activity related to the presence (vs. absence) of distractor faces (e.g., in the "fusiform face area"; Kanwisher, McDermott, & Chun, 1997) was significantly greater under conditions of high (vs. low) working memory load. These results provide encouraging evidence for our proposed role of working memory in selective attention.

Overview of the Present Experiments

To examine the hypothesis that distractor processing in selective attention tasks depends on the level and type of load involved, we combined a selective attention task with a short-term recognition memory task in which we manipulated working memory load by

varying the memory set size (Sternberg, 1966). For the selective attention task, we used the flanker response-competition task (Eriksen & Eriksen, 1974). Subjects made speeded choice responses to a target presented in the center of the display while attempting to ignore an irrelevant distractor letter presented at the periphery. Compatibility of target and distractor responses was manipulated so that distractors were either compatible with the target (the same as the target letter) or incompatible with the target (the alternative target letter). Slower RTs to the targets in the incompatible versus the compatible conditions served to indicate that the subjects failed to ignore the distractors.

In the experiments on working memory load (Experiments 1–3), the selective attention task was presented during the retention interval of a short-term memory recognition task. On each trial, the selective attention task was preceded by a memory set and followed by a memory probe. Subjects were asked to indicate whether the memory probe digit was present or absent in the preceding memory set. Working memory load was manipulated by varying the memory set size between one digit (low working memory load) and six digits (high working memory load), and distractor compatibility effects in the selective attention task were compared between conditions of low and high working memory load. The identity of digits in the memory set differed on each trial in both conditions of memory set size to ensure that any process of recency detection (e.g., Monsell, 1978) that recognition may involve would still require active maintenance as well.[3]

In Experiment 3, we manipulated both working memory load (by varying the memory set size) and perceptual load (by varying the number of letters among which the target had to be searched for in the selective attention task). In Experiments 4–5, we asked whether the demand to coordinate the selective attention flanker task with a short-term memory task might in itself load cognitive control and hence result in greater distractor interference. In these experiments, we compared distractor effects in the selective attention task in single-task conditions and dual-task conditions in which subjects performed the working memory task as well. Important to note is that in these experiments, subjects completed the short-term memory task before starting the selective attention task on each trial, so the main difference between the single- and dual-task conditions was in terms of task coordination rather than the number of items that needed to be retained in short-term memory.

We predicted that manipulations of load on working memory or on task coordination would result in greater intrusions of irrelevant distractors in the selective attention task. By contrast, we predicted that high perceptual load in the processing of relevant stimuli of the attentional task would reduce distractor interference, the opposite to the prediction for high cognitive control load.

Experiment 1

Method

Subjects. Eleven students from Cambridge University participated. All of the subjects in all of the experiments reported in this article had normal or corrected-to-normal vision, and all were paid £4 ($7.25) for their participation. The data from 1 subject were excluded from analysis because of a failure in computer recording of his responses.

Stimuli and apparatus. The experiment was run on an IBM-compatible computer attached to a 15-in SVGA monitor and a standard keyboard.

Micro Experimental Laboratory (MEL; Schneider, 1988) software was used to create the stimuli, run the experiment, and collect the data. All stimuli were light gray (No. 7 in the MEL color palette). The digit display of the memory task consisted of six digits, each subtending a visual angle of 0.57° horizontally and 1.05° vertically at a viewing distance of 60 cm. These digits were presented equally spaced in a horizontal row (subtending 5.43° from edge to edge) at the center of the display. For the memory set in the low-load condition, one digit was presented at the center of the display. For the masking array, six asterisks positioned in the positions of the digits in the memory set of the high working memory load condition were used. The target letter in the selective attention task subtended a visual angle of 0.48° horizontally and 0.67° vertically and was equally likely to be either *x* or *z*, presented in lowercase equiprobably in any of six possible positions along a central horizontal row subtending 4.9°. A distractor letter subtending a visual angle of 0.57° horizontally and 1.05° vertically was presented above or below the central position and was equiprobably compatible (e.g., an *X* when the target was an *x*), incompatible (e.g., an *X* when the target was a *z*), or neutral (the letter *N*). The combinations of target identities, target positions, distractor identities, and distractor positions were counterbalanced so that each target in any given position was equally likely to be presented with any distractor in either of the two distractor positions. The digits in the memory set were chosen at random from 1 to 9, and each digit was equally likely to be present in the memory set of each load condition. The order of six digits in the memory set of the high working memory load was random, with the constraint that no more than two digits were presented in sequential order. For the memory probe, one digit was presented in the center. Probe digits were equally likely to be present or absent in the trial's set and equally likely to probe any of the six possible memory set positions in the trials of high working memory. In addition, probe condition (present or absent) was counterbalanced across trials so that it was equally likely to follow a compatible, incompatible, or neutral condition of the selective attention task for both target and distractor identities. Seventy-two trials were created for each condition of working memory load according to these specifications.

Procedure. Each trial consisted of the following sequence. A fixation dot was displayed for 500 ms, followed by a memory set that was presented for 500 ms in the low-load condition or for 2 s in the high-load condition.[4] A masking array was then presented for 750 ms in the low working memory load condition or for 2.5 s in the high working memory load condition. A shorter retention interval was used in the low working memory load condition than in the high working memory load condition to prevent the possibility that a more enduring passive trace would be formed for the one digit presented during a long (2.5 s) retention interval (given for the high working memory load task) and thus to make it more likely that the low working memory load condition would still impose some load on working memory.

The masking array was followed by a fixation point presented for 500 ms and replaced by brief presentation (100 ms) of the selective attention task display, consisting of a target letter and a distractor letter. Subjects were required to respond by using their right hand to press *0* on the numeric keypad if the target letter on this display was a *z* or *2* if the target was an *x*. Subjects were warned of the potentially disruptive effect of the distractor presented in the selective attention task and were strongly encouraged to ignore it. A time window of 2 s was provided for responses in the selective attention task. After the response to the selective attention task (or on termination of the 2-s time window, in cases of a missed response), a memory probe was presented and remained displayed for 3 s or until the

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[3] We thank Stephen Monsell for his helpful comment on this point.

[4] The presentation durations of the memory sets in all of the experiments were chosen to provide sufficient time to read all of the set digits, as confirmed by pilot testing.

subject responded by pressing *q* to indicate that the probe digit was present in the trial's memory set or *w* to indicate that the probe digit was absent from the trial's memory set on the computer keyboard. A 500-ms computer tone immediately followed all incorrect responses and was also presented if subjects failed to respond within the given time window to either task.

The conditions of working memory load were blocked.[5] Each block consisted of 72 trials. The order of presentation alternated between blocks of high working memory load and blocks of low working memory load. Half the subjects began with a high working memory load block, and half began with a low working memory load block. Six experimental blocks were run, preceded by two blocks of 16 example trials from each load condition that were presented in the same order as were the experimental blocks.

Results

Memory task. Trials with RTs under 100 ms and over 2 s were excluded from analysis. These cutoff points were used for all the RT analyses (in both the memory and the selective attention tasks) reported in this article and never resulted in a loss of more than 2% of responses. Two-way within-subject analyses of variance (ANOVAs) on the RTs of correct memory probe responses and on the error rates as a function of working memory load (low, high) and probe type (present, absent) revealed a significant main effect for working memory load on RTs, $F(1, 9) = 81.58$, $MSE = 10,110$, $p < .001$, $\eta^2 = .901$, and a supporting trend in the errors, $F(1, 9) = 3.08$, $MSE = 0.002$, $p = .10$, $\eta^2 = .255$; see Table 1. These findings confirm that our manipulation of memory set size was effective in increasing memory load. RTs also tended to be slower when the probe was absent than when it was present, $F(1, 9) = 5.14$, $MSE = 8,257$, $p = .05$, $\eta^2 = .363$. There were no other significant effects in either analysis (all other ps > .10).

Selective attention task. Our primary hypothesis concerns the effects of working memory load on the efficiency of distractor rejection in the selective attention task. Table 2 presents RTs and error rates in the selective attention task as a function of the experimental factors. Only trials on which the subjects were correct on the memory task were included in the analysis of results for the selective attention task, and only trials on which the subjects were correct on both the memory task and the attention task were included in the analyses of the selective attention task RTs. This inclusion criterion was used for the analyses of results in all

Table 1

Experiment 1: Mean Correct Reaction Times (in Milliseconds) and Error Rates on the Memory Task as a Function of Working Memory Load and Probe Condition

| | Probe condition | | | |
| | Present | | Absent | |
Working memory load	M	SD	M	SD
Low				
M	618	129	691	103
%E	5	3	5	2
High				
M	912	167	969	210
%E	9	5	7	6

Note. %E = error rate calculated as a percentage.

Table 2

Experiment 1: Mean Correct Reaction Times (in Milliseconds) and Error Rates on the Selective Attention Task as a Function of Working Memory Load and Distractor Compatibility

| | Distractor compatibility | | | | | | |
| Working memory load | I | | C | | | N | |
	M	SD	M	SD	I − C	M	SD
Low							
M	1,003	183	863	152	140	882	137
%E	8	6	3	2	5	6	5
High							
M	1,016	199	823	129	193	879	170
%E	12	9	4	4	8	4	4

Note. I = incompatible; C = compatible; N = neutral; %E = error rate calculated as a percentage.

subsequent experiments. A two-way within-subject ANOVA performed on the selective attention task RTs as a function of working memory load (low load, high load) and distractor compatibility (incompatible, compatible) revealed a main effect of distractor compatibility, $F(1, 9) = 29.8$, $MSE = 10,237$, $p < .001$, $\eta^2 = .749$, indicating that once again subjects failed to ignore the distractor, as expected for this low perceptual load situation. There was no main effect of working memory load on RTs in the selective attention task ($F < 1$). Critically, however, there was a significant interaction between working memory load and distractor compatibility, $F(1, 9) = 5.16$, $MSE = 1,496$, $p < .05$, $\eta^2 = .340$. Although distractor compatibility effects were significant in both low-load, $t(9) = 4.75$, $SEM = 29.48$, $p < .01$ (two-tailed, as in the remainder of the article, unless otherwise stated), and high-load conditions, $t(9) = 5.43$, $SEM = 35.56$, $p < .001$, they were significantly increased under high load, as we predicted.

A similar two-way within-subject ANOVA conducted on the error rates revealed a main effect for distractor compatibility, $F(1, 9) = 15.84$, $MSE = 0.0029$, $p < .003$, $\eta^2 = .613$, and a trend for a main effect of working memory load, $F(1, 9) = 3.84$, $MSE = 0.0019$, $p < .08$, $\eta^2 = .277$. The interaction between working memory load and distractor compatibility was not significant in the error rate analysis ($F < 1$); however, the numerical trend for greater distractor effects in high versus low working memory load (see Table 2) was consistent with the RTs.

To investigate whether working memory load had a different effect on each component of the distractor compatibility effects (interference and facilitation), we calculated the magnitude of the interference effect (by computing the difference between incompatible and neutral conditions) and the magnitude of the facilitation effect (by computing the difference between compatible and neutral conditions) for each participant. These differences were

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[5] The conditions of working memory load were blocked because we suspected that intermixing trials of different memory load in one block would result in a general increase in load on cognitive control (as such intermixed blocks would require switching between the different types of trials). Such a general increase in cognitive control load might blur the difference between the conditions of working memory load and hence reduce the potency of the manipulation of current interest.

then entered into a 2 (component: interference, facilitation) × 2 (working memory load: low, high) within-subjects ANOVA. The results of this ANOVA revealed significant main effects of component, $F(1, 9) = 14.04$, $MSE = 6,558$, $p < .01$, $\eta^2 = .584$, and of working memory load, $F(1, 9) = 5.16$, $MSE = 1,496$, $p < .05$, $\eta^2 = .340$, but no interaction of load and component ($F < 1$). Thus, these results showed a general effect of increase in distractor compatibility effects by working memory load but did not highlight any different effect of working memory load on interference by incompatible distractors or facilitation by compatible distractors.

Discussion

The first experiment provides preliminary support for our hypothesis that the efficiency of selective attention depends on the extent to which working memory is available for attention. Although the irrelevant distractors were perceived under both conditions of working memory load (as we anticipated for the situation of low perceptual load in this experiment; see Lavie, 1995), distractor compatibility effects were significantly greater under conditions of high versus low working memory load. Notice that this is a very specific effect of working memory load on selective attention, which is exactly as predicted from our hypothesis.

Analysis of the effects of working memory load on the different components of the distractor compatibility effect did not reveal any significant difference in the effects of working memory load on interference (from incompatible vs. neutral distractors) and facilitation (from compatible vs. neutral distractors). Instead, the results simply show a more general increase in the processing of irrelevant distractors under high (vs. low) working memory load.

We note that in addition to the increased compatibility effects seen under high working memory load conditions, the overall size of distractor compatibility effects found in this experiment was rather large. For example, even under the condition of low working memory load, the mean distractor effect was 140 ms. In contrast, the typical range of distractor effect size in previous flanker studies tends to be around 10–40 ms (e.g., Eriksen & Eriksen, 1974; Yantis & Johnston, 1990). This difference in the general size of distractor compatibility effects may be due to the fact that the flanker task in this experiment was always performed under dual-task conditions, whereas previous flanker tasks were typically conducted under single-task conditions. The issue of whether the additional demand to coordinate two tasks imposes on cognitive control functions that are also involved in the control of selective attention (and may therefore be sufficient to increase distractor intrusions) will be addressed more directly in Experiments 4 and 5.

Experiment 2

Experiment 2 was conducted to address a possible alternative account for the results of Experiment 1 in terms of a difference in the processes of rehearsal between the conditions of working memory load. Active maintenance of verbal material in short-term memory is well-known to involve rehearsal; it is thus highly likely that the conditions of high working memory load in the present study involved rehearsal. However, it is less clear that the condition of low working memory load involved rehearsal to the same extent, as maintaining a single digit is far less demanding than maintaining six digits is. Differences in the extent to which rehearsal was used in the different levels of working memory load could suggest alternative accounts of our findings. For example, the extent to which the memory task exerts some articulatory suppression effects (Baddeley & Hitch, 1974) on the interleaved letter-flanker task may vary. Specifically, rehearsal of verbal material is known to involve articulation. As our memory and attentional tasks both involved verbal material (digits and letters), covert articulation of the memory digits during performance of the selective attention task may have blocked articulation of the attention task letters. Moreover, if high working memory load involved more such articulatory suppression effects than did low working memory load, then the increased distractor effects in the high (vs. low) working memory load conditions might somehow be the result of articulatory suppression rather than load on working memory per se. For example, suppression of the verbal code that may have been used for target responses may have rendered these targets more open to distractor intrusions.

Therefore, in Experiment 2, we asked subjects to overtly rehearse the memory sets into a tape recorder throughout the retention interval until presentation of the probe in both conditions of working memory load, in a task that was otherwise similar to that used in Experiment 1. In addition, to verify that a difference in duration of retention intervals between low and high working memory load (as in Experiment 1) cannot account for the results, we now used the same time intervals for both memory sets. Finally, as the comparisons of the distractor effects from the incompatible and compatible conditions to a neutral condition in Experiment 1 did not reveal any significant difference in susceptibility to effects of working memory load, we did not include a neutral distractor condition any longer.

Method

Subjects. Fifteen students from Cambridge University participated. None of the subjects had participated in Experiment 1, and 1 subject's data were excluded from analysis because his performance on the selective attention task was at chance (error rate = 54%).

Stimuli and apparatus. The apparatus and software used were the same as those used for the previous experiment. The digit displays of the memory task consisted of either one or six digits and were identical to the digit displays used in Experiment 1. The selective attention task displays used were also identical to those used in Experiment 1, with one exception: No neutral letters were used as distractor letters. The memory probe was either present or absent and was presented in the center of the screen in a green color (No. 10 in the MEL color palette).[6] Seventy-two displays were created for each condition of memory load according to these specifications.

Procedure. The procedure was similar to that from Experiment 1 except for the following changes. The memory set was presented for 750 ms in the low working memory load condition and for 1,500 ms in the high working memory load condition. The masking display that followed was presented for 1,250 ms in both conditions and was in turn followed by a 500-ms fixation dot that was replaced by the selective attention task display as before. Subjects were instructed to rehearse the digits in the memory set out loud into a tape recorder until the presentation of the memory probe in both conditions of memory load.

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[6] Following comments of subjects in Experiment 1, a color difference between the memory set and memory probe digits was introduced to ensure that the difference between these displays is clear.

Results

Memory task. As in Experiment 1, two-way within-subject ANOVAs on the RTs of correct memory probe responses and on the error rates as a function of working memory load (low, high) and probe type (present, absent) revealed main effects for working memory load—$F(1, 13) = 69.16$, $MSE = 4,491$, $p < .001$, $\eta^2 = .900$, for the RTs; $F(1, 13) = 6.97$, $MSE = 0.0009$, $p < .02$, $\eta^2 = .523$, for the error rates—confirming that the manipulation of memory set size was effective in increasing the load on working memory. In addition, absent probes resulted in slower RTs than present probes did, $F(1, 13) = 13.72$, $MSE = 1,330$, $p < .003$, $\eta^2 = .712$. There was no interaction between probe type and working memory load in the RTs ($F < 1$). Error rates were greater for present than for absent probes, $F(1, 13) = 5.86$, $MSE = 0.004$, $p < .031$, $\eta^2 = .299$ (see Table 3), but this result was qualified by an interaction between probe type and working memory load, $F(1, 13) = 12.34$, $MSE = 0.004$, $p < .004$, $\eta^2 = .658$. The interaction indicated a greater increase in the number of misses in response to present probes by load (5% increase), $t(13) = 3.06$, $SEM = 0.0021$, $p < .01$, than in the number of false positive responses to the absent probes (1% increase; $t < 1$). This may not be surprising, as with a greater set size, the chances for misses are clearly increased (any digit in the six-digit set can be missed), whereas the chances for false positive reports may be more affected by general factors such as guessing criterion rather than purely by memory set size.

Selective attention task. Table 4 presents RTs and error rates in the selective attention task as a function of the experimental factors. A two-way within-subject ANOVA performed on the selective attention task RTs as a function of working memory load (low, high) and distractor compatibility (incompatible, compatible) revealed again a main effect of distractor compatibility, $F(1, 13) = 21.07$, $MSE = 1,714$, $p < .001$, $\eta^2 = .618$, indicating that subjects failed to ignore the distractor as expected for this low perceptual load situation. There was also a small but significant main effect of working memory load on the selective attention task RTs, $F(1, 13) = 6.05$, $MSE = 4,496$, $p < .03$, $\eta^2 = .317$. The critical finding was a significant interaction between working memory load and distractor compatibility, $F(1, 13) = 4.66$, $MSE = 383$, $p < .05$, $\eta^2 = .264$. Once again, although distractor compatibility effects

Table 3
Experiment 2: Mean Correct Reaction Times (in Milliseconds) and Error Rates on the Memory Task as a Function of Working Memory Load and Probe Condition

| | Probe condition | | | |
| | Present | | Absent | |
Working memory load	M	SD	M	SD
Low				
M	635	226	705	232
%E	5	5	5	3
High				
M	856	264	915	246
%E	10	5	6	4

Note. %E = error rate calculated as a percentage.

Table 4
Experiment 2: Mean Correct Reaction Times (in Milliseconds) and Error Rates on the Selective Attention Task as a Function of Working Memory Load and Distractor Compatibility

| | Distractor compatibility | | | | |
| | I | | C | | |
Working memory load	M	SD	M	SD	I − C
Low					
M	810	143	771	149	39
%E	5	5	3	3	2
High					
M	865	176	804	166	61
%E	6	5	4	5	2

Note. I = incompatible; C = compatible; %E = error rate calculated as a percentage.

were significant in both low-load, $t(13) = 2.93$, $SEM = 13.50$, $p < .05$, and high-load conditions, $t(13) = 5.73$, $SEM = 10.83$, $p < .001$, they were significantly increased under high load, as we predicted.

The small increase in overall RTs in the high-load condition is unlikely to account for the greater distractor effect in this condition, as the distractor effect was still greater in the high- versus low-load condition when calculated as a percentage of the overall RT per individual in each working memory load condition. The distractor interference effect was 7.5% of the mean RT for the high-load condition and 5.25% of the mean RT for the low-load condition, and this difference was significant, $t(13) = 2.08$, $SEM = 0.0107$, $p < .05$ (one tailed).

A similar two-way within-subject ANOVA carried out on the error rates replicated the main effect for distractor compatibility, $F(1, 13) = 9.79$, $MSE = 0.0005$, $p < .01$, $\eta^2 = .412$. There were no other significant effects in this analysis ($F < 1$). However, as can be seen in Table 4, error rates did not show any trade-off with RTs.

Discussion

Experiment 2 demonstrated again that higher working memory load results in greater interference by an irrelevant distractor on performance of a selective attention task. As subjects were now forced to rehearse the digits out loud in both conditions of working memory load, this experiment allows us to rule out any alternative accounts in terms of the involvement of rehearsal and associated processes (e.g., articulatory suppression effects on the selective attention task) in the high but not in the low working memory load conditions.

It is interesting that in both conditions of working memory load, the overall level of distractor effects was generally lower than that found in Experiment 1. This may be due to a general effect of articulatory suppression on the interference from the distractor letters at both working memory loads. Such effects of articulation are consistent with previous findings that articulatory suppression reduces distractor interference in Stroop-like tasks (e.g., Martin, 1978). Because this issue is peripheral to our main focus on the

effects of working memory load on selective attention, we did not pursue it further.

Experiment 3

The purpose of Experiment 3 was to directly contrast the effects on selective attention of working memory load and perceptual load. The finding that high working memory load increases distractor interference in the first two experiments is in sharp contrast with previous findings that high perceptual load decreases distractor interference (e.g., Lavie, 1995; Lavie & Cox, 1997; Lavie & Fox, 2000). This contrast between the effects of different types of load on distractor processing is exactly as predicted by our claim that the efficiency of selective attention depends on two mechanisms of control: (a) a perceptual early selection mechanism that allows for reduced distractor perception in situations of high perceptual load that exhaust perceptual capacity in processing relevant stimuli and (b) a cognitive control mechanism that acts to ensure the attentional selection of relevant over irrelevant stimuli in accordance with current stimulus-processing priorities, even when irrelevant stimuli are perceived, as long as cognitive control functions (such as working memory) are available for monitoring selective attention.

However, so far the evidence for the contrasting effects of working memory load and perceptual load on distractor processing relies on comparisons between different studies with different experimental methods. For example, previous perceptual load studies have typically involved a single-task situation, whereas our current experiments involve a dual-task situation. Thus, in Experiment 3, we examined the effects of both perceptual load and working memory load on distractor interference using the interleaved-tasks method.

Working memory load and perceptual load were manipulated in an orthogonal design. Working memory load was manipulated as in Experiments 1 and 2 by requesting subjects to memorize either one or six different digits on each trial. Perceptual load in the selective attention task was manipulated by varying the relevant set size. In conditions of low perceptual load, the selective attention task displays were similar to those in the previous experiments: A single target letter was presented in one of six central positions (together with an irrelevant distractor in the periphery). In conditions of high perceptual load, five nontarget letters were presented in the other central positions. The nontarget letters were all response neutral (i.e., letters that were not associated with any response in this task) and only served to force subjects to search for the target letter among them. This manipulation of relevant set size has previously been used successfully to demonstrate the effect of perceptual load on selective attention in a large number of experiments (e.g., Lavie, 1995; Lavie & Cox, 1997; Lavie & Fox, 2000). Our main prediction concerned the opposite effects that perceptual load and working memory load should have on distractor effects in the selective attention task. Whereas working memory load was expected to increase distractor effects, perceptual load was expected to reduce distractor effects.

Method

Subjects. Sixteen students from University College London participated. The data from 3 subjects, whose accuracy rates were near chance in either the attention task or the memory task, were excluded from analysis.

Stimuli and apparatus. The apparatus was the same as that used in Experiment 1. The working memory task was similar to that used in Experiment 1, except we used green digits for the memory probes (as in Experiment 2). The selective attention task was similar to that used in Experiment 1, except we included a high perceptual load condition, in which the target letter was presented among five nontargets that were the same size as the target and equally spaced in a central row subtending 4.9°. Nontargets were always the letters *S, K, V, J* and *R*, presented in uppercase. Targets were presented equally often in each of the six target locations, and each nontarget was randomly allocated to one of the five remaining locations on each trial.

Procedure. The procedure was similar to that used in Experiment 2, except for the following changes. Subjects were encouraged to rehearse the digits covertly but were not requested to articulate the sets out loud. The memory set was presented for 250 ms (in the low working memory load condition) or 1,500 ms (in the high working memory load condition). The masking display was presented for 1,250 ms (in the low working memory load condition) or 2,500 ms (in the high working memory load condition). The memory probe that came after the selective attention task was followed by a 950-ms intertrial interval in the low working memory load condition and a 750-ms intertrial interval in the high working memory load condition. The combinations of conditions of working memory load and perceptual load were blocked. There were four block types: high working memory load and high perceptual load (H/H), high working memory load and low perceptual load (H/L), low working memory load and high perceptual load (L/H), and low working memory load and low perceptual load (L/L). Subjects performed eight blocks of 72 trials each. They alternated between the four block types in one of four possible orders of presentation that we constrained by grouping blocks of the same working memory load together so that the first four blocks were in one of the following orders: H/H, H/L, L/H, L/L; H/L, H/H, L/L, L/H; L/H, L/L, H/H, H/L; or L/L, L/H, H/L, H/H. The subsequent four blocks per each subject were run in the same order as the first four blocks were. The presentation order was counterbalanced between participants so that each order was run on one quarter of the subjects. Prior to the experimental session, each subject completed four blocks of 12 practice trials, one from each block type.

Results

Memory performance. A two-way within-subject ANOVA on the memory probe RTs as a function of working memory load (low, high) and probe type (present vs. absent) revealed a significant increase in the RTs by high (vs. low) working memory load, $F(1, 12) = 155.51, MSE = 5,038, p < .001, \eta^2 = .928$. RTs were also slower to absent compared with present probes, $F(1, 12) = 4.72, MSE = 7,446, p = .051, \eta^2 = .282$; see Table 5. There was no interaction between working memory load and probe type ($F < 1$). A similar ANOVA on the error rates showed a significant increase in the number of errors under high (vs. low) working memory load, $F(1, 12) = 5.81, MSE = 0.0053, p < .05, \eta^2 = .326$. There were no other significant effects in the error data ($p > .10$ for all other effects). These findings confirm that working memory load was effectively manipulated with our manipulation of memory set size. In further three-way ANOVAs of RTs and error rates including the factor of perceptual load in addition to working memory load and probe type, there were no effects of perceptual load on memory performance (for all effects involving perceptual load, $F < 1$).

Selective attention task. Table 6 presents RTs and error rates in the selective attention task as a function of the experimental factors. A three-way within-subject ANOVA was performed on the selective attention task RTs as a function of working memory

Table 5

Experiment 3: Mean Correct Reaction Times (in Milliseconds) and Error Rates on the Memory Task as a Function of Working Memory Load and Probe Condition

| | Probe condition | | | |
| | Present | | Absent | |
Working memory load	M	SD	M	SD
Low				
M	630	120	676	147
%E	16	15	14	10
High				
M	870	166	928	150
%E	24	18	17	12

Note. %E = error rate calculated as a percentage.

load (low, high), perceptual load (low, high), and distractor compatibility (incompatible, compatible). This ANOVA revealed slower RTs in high perceptual load than in low perceptual load, $F(1, 12) = 10.67$, $MSE = 15,584$, $p < .01$, $\eta^2 = .471$. This effect confirms that perceptual load was successfully manipulated and is consistent with previous results in similar visual search paradigms (e.g., Lavie & Cox, 1997). There was no effect of working memory load on RTs in the selective attention task ($p > .10$). There was a main effect of distractor compatibility, $F(1, 12) = 40.42$, $MSE = 1,774$, $p < .001$, $\eta^2 = .771$; however, this effect was qualified by two-way interactions with working memory load, $F(1, 12) = 9.63$, $MSE = 1,142$, $p < .01$, $\eta^2 = .445$, and with perceptual load, $F(1, 12) = 14.70$, $MSE = 2,736$, $p < .01$, $\eta^2 = .550$. The pattern of the Working Memory Load × Distractor Compatibility interaction was as before: distractor effects in conditions of low working memory load ($M = 32$ ms) were significantly increased by high working memory load ($M = 73$ ms). In contrast but similar to previous results in studies of perceptual load (e.g., Lavie, 1995), the interaction with perceptual load showed an opposite pattern: Distractor effects in conditions of low perceptual load ($M = 92$ ms) were significantly decreased by high perceptual load ($M = 14$ ms).

The three-way interaction between perceptual load, working memory load, and distractor compatibility was not significant ($F < 1$). As can also be seen from Table 6, working memory load increased distractor effects to a similar extent under low perceptual load ($M = 39$-ms increase) and under high perceptual load ($M = 43$-ms increase), and perceptual load reduced distractor effects to a similar extent under low working memory load ($M = 80$-ms decrease) and under high working memory load ($M = 76$-ms decrease).

A similar three-way within-subject ANOVA was conducted on the error rates as a function of distractor compatibility, working memory load, and perceptual load. This ANOVA replicated the main effect of distractor compatibility, $F(1, 12) = 19.83$, $MSE = 0.00096$, $p < .001$, $\eta^2 = .623$, found in the RTs. Similar to the RT results, error results showed that distractor effects in high working memory load ($M = 5\%$) were significantly greater, $F(1, 12) = 7.08$, $MSE = 0.0014$, $p < .03$, $\eta^2 = .371$, than they were in low working memory load ($M = 2\%$). No other main effects or interactions were significant in the error rate analysis ($F = 1.27$ for the main effect of perceptual load, $F < 1$ for all other effects).

Discussion

The results of Experiment 3 clearly establish, within the same study, that perceptual load and working memory load have opposite effects on selective attention. Consistent with Experiments 1–2, working memory load was again found to increase distractor interference in the selective attention task. By contrast, high perceptual load significantly decreased distractor interference, a result that is consistent with previous findings in perceptual load studies (for reviews, see Lavie, 2000, 2001). The contrast between the effects of perceptual load and of working memory load on distractor interference provides support for our hypothesis that selective attention involves two dissociable mechanisms of control against distractor intrusions: a perceptual selection mechanism that reduces distractor perception in situations of high perceptual load and a cognitive control mechanism that acts to ensure that attention is allocated in accordance with current stimulus-processing priorities and thus minimizes intrusions of irrelevant distractors as long as working memory is available to actively maintain the current priority set (in situations of low working memory load).

Table 6

Experiment 3: Mean Correct Reaction Times (in Milliseconds) and Error Rates on the Selective Attention Task as a Function of Working Memory Load, Perceptual Load, and Distractor Compatibility

| | Low perceptual load | | | | | High perceptual load | | | | |
| | I | | C | | | I | | C | | |
Working memory load	M	SD	M	SD	I − C	M	SD	M	SD	I − C
Low working memory load										
M	841	129	769	110	72	877	135	885	139	−8
%E	11	10	10	10	1	13	7	13	7	0
High working memory load										
M	885	146	774	136	111	931	119	896	113	35
%E	13	12	8	6	5	15	5	11	6	4

Note. I = incompatible; C = compatible; %E = error rate calculated as a percentage.

The finding that the effects of perceptual load and working memory load on selective attention were additive suggests that the effect of each of these manipulations does not depend on the effect of the other. This is what one might expect given the different natures of processes that are affected by these different types of load. Whereas perceptual load mainly affects early perceptual processes, working memory load affects higher cognitive processes involved in active maintenance of stimuli in working memory. Thus, the effects of perceptual load and working memory load involve different levels of processes that are also known to involve dissociable neural substrates in the posterior visual cortex (perceptual load) versus more anterior cortices (working memory load).

This pattern of findings also clearly shows that successful prevention of distractor processing depends on both working memory load (being low) and perceptual load (being high). Low working memory load is important to allow for active maintenance of stimulus processing priorities throughout performance of the selective attention task, regardless of the level of perceptual load in it. However, appropriate allocation of attention to relevant stimuli (in situations of low working memory load) cannot on its own reduce the processing of irrelevant stimuli. High perceptual load is needed too, because as long as perceptual load is low, spare capacity from processing the relevant stimuli will spill over to the processing of irrelevant stimuli.

Experiments 4 and 5: The Role of Dual-Task Coordination in Selective Attention

The experiments reported so far establish the important role played by working memory in determining interference by irrelevant distractors. However, these experiments also revealed unusually large distractor effects even under conditions of negligible working memory load, as long as perceptual load was low and articulatory suppression was not involved (cf. Experiment 2). For example, in the conditions of low perceptual load and low working memory load of Experiments 1 and 3, distractor effects were 140 ms and 72 ms, respectively. In contrast, distractor effects in previous studies using a similar flanker task are around 10–40 ms (e.g., Lavie, 1995; Yantis & Johnston, 1990). However, these previous experiments were typically conducted under single-task conditions, whereas in our paradigm, the flanker task was interleaved with a memory task in a variation of a dual-task paradigm. It is possible that the requirement to coordinate two tasks in the present experiments has drawn on the capacity needed for cognitive control mechanisms that serve to actively maintain task performance in accordance with stimulus-processing priorities and has thus led to greater intrusions of irrelevant distractors in the selective attention task, even under conditions of low working memory load.

Indeed, the coordination of multiple tasks certainly requires active control of processing priorities in accordance with the different requirements of each task and is known to be associated with frontal cognitive control processes (e.g., Della Sala, Baddeley, Papagano, & Spinnler, 1995; D'Esposito et al., 1995; Miller & Cohen, 2001; Shallice & Burgess, 1996). Accordingly, we hypothesized that the requirement to coordinate the two tasks of memory and selective attention in our interleaved design may have loaded another component of cognitive control that is also required for stimulus prioritization and thus resulted in a general decrease in the ability to control interference from irrelevant distractors in the selective attention task. This hypothesis was tested in Experiments 4 and 5.

Experiment 4

In the following experiments, we test whether engaging cognitive control in dual-task coordination affects the interference from irrelevant distractors in performance of a selective attention task even when the short-term memory task and selective attention task are performed without any overlap but in close succession. This was achieved by requiring on each trial that the short-term memory task be completed before the selective attention task was initiated. Alternating between the two tasks (i.e., task switching) should still impose a demand on dual-task coordination, as it requires monitoring and sequencing of behavioral subgoals (e.g., Duncan, 1995, 1996) and the continuous reconfiguration of current attentional priorities as in other task-switching paradigms (e.g., Rogers & Monsell, 1995). Therefore, we expected that demands on cognitive control of processing priorities imposed by such task coordination would reduce the availability of such cognitive control for performance of the selective attention task and thus result in greater interference by irrelevant distractors.

The next experiment was similar to Experiment 1, but now the subjects delivered their response to the memory probe before the selective attention task. As a consequence, there was no need to retain any component of the memory task or prepare a response to it while performing the selective attention task. Stimuli for a memory task and a selective attention task were presented in both the single-task condition and the dual-task condition. However, a response to the memory task was only required in the dual-task condition. Presentation of the memory set in the single-task condition, with an exposure duration similar to that in the dual-task condition, was retained to keep the single- and dual-task conditions visually similar to one another. Therefore, the main difference between the single- and dual-task conditions was only whether the memory task was performed.

In Experiment 4, we used a memory set size of six items; in the short-term memory task and in Experiment 5, we used a memory set of one item. We hypothesized that the effects of task coordination on selective attention would be similar across both experiments irrespective of their difference in memory set size, because subjects no longer had to keep this set in memory while performing the selective attention task in these experiments.

Method

Subjects. Ten new students from Cambridge University participated.

Stimuli, apparatus, and procedure. The apparatus and software used to create the stimuli, run the experiment, and collect the data were the same as in the previous experiments. The dimensions and characteristics of the stimuli for both the memory task and the selective attention task were the same as those in the high working memory load condition of Experiment 1. The procedure was similar to Experiment 1 except for the following changes. The fixation point was presented for 750 ms; the following six-digit memory set was presented for 1 s in the single-task condition or for 2 s in the dual-task condition. The masking display was presented for 750 ms, then the probe display was presented for 500 ms in both the single-task and the dual-task conditions. The probe item was a digit in the dual-task condition and an asterisk in the single-task condition (to prevent

any temptation to mentally perform the memory task in the single-task condition). In the dual-task condition, subjects were requested to respond to the probe on its appearance. The selective attention task immediately followed the memory probe in the single-task condition or the response to the memory probe in the dual-task condition. As in the previous experiments, a 500-ms fixation point was presented at the start of the selective attention task. The single- and dual-task trials were presented in six alternating blocks of 72 trials each, and each subject had two practice blocks of 16 trials each before the beginning of the experiment. Half the subjects began with a single-task block, and the other half began with a dual-task block.

Results

Memory task. The mean RT of the correct responses to the memory probe in the dual-task conditions of this experiment was 856 ms ($SD = 121$), and the mean error rate was 7% ($SD = 4\%$). Note that this mean RT is consistent with the typical range seen in the high working memory load conditions of the earlier experiments.

Selective attention task. Mean RTs and accuracy rates in the selective attention task were calculated for each subject as a function of the experimental factors and are presented in Table 7. A two-way within-subject ANOVA of distractor compatibility (incompatible vs. compatible) and task (single vs. dual) performed on the selective attention task RTs showed again a significant main effect for distractor compatibility, $F(1, 9) = 26.42$, $MSE = 1,465$, $p < .001$, $\eta^2 = .746$. There was a nonsignificant trend for a main effect of task condition, $F(1, 9) = 3.12$, $p > .10$. More important, there was a significant interaction between distractor compatibility and task, $F(1, 9) = 11.72$, $MSE = 318$, $p < .01$, $\eta^2 = .556$, showing that although distractor compatibility effects were significant in both the single-task condition, $t(9) = 3.8$, $SEM = 11.41$, $p < .01$, and the dual-task condition, $t(9) = 4.95$, $SEM = 14.66$, $p < .001$, distractor effects were significantly greater in the dual-task condition than in the single-task condition, as we predicted.

A similar two-way within-subject ANOVA on the error rates in the selective attention task showed only a main effect for distractor compatibility, $F(1, 9) = 6.68$, $MSE = 0.0013$, $p < .05$, $\eta^2 = .426$. There was no main effect for task and no significant interaction between distractor compatibility and task ($F < 1$ for both).

Table 7
Experiment 4: Mean Correct Reaction Times (in Milliseconds) and Error Rates on the Selective Attention Task as a Function of Task Condition and Distractor Compatibility

| | Distractor compatibility | | | | |
| | I | | C | | |
Task condition	M	SD	M	SD	I − C
Single					
M	641	92	606	93	35
%E	7	8	3	3	4
Dual					
M	688	167	626	143	62
%E	5	5	4	4	1

Note. I = incompatible; C = compatible; %E = error rate calculated as a percentage.

Discussion

This experiment revealed a specific effect of dual-task coordination on selective attention that was exactly as predicted. Performance of the selective attention task suffered from greater distractor interference under dual-task conditions compared with the single-task conditions. Whereas all models of dual-task coordination (as assessed both in the dual-task paradigm and in the task-shifting paradigm) predict a general cost in performance (expressed, e.g., in slowing of overall RTs) of the dual-task (switching) conditions versus single task (no-switching) conditions, the finding of greater distractor effects in the selective attention task in the dual- versus single-task conditions was specifically as predicted from our hypothesis. This finding is also consistent with our suggestion that the unusually large distractor effects in the conditions with low working memory load (as well as low perceptual load) of our previous experiments may have been due to the demand to coordinate the memory task and the attention task in our paradigm. Indeed, the single-task condition of the present experiment produced compatibility effects averaging 35 ms, which are consistent with previous findings in flanker tasks performed in a single-task situation (e.g., Eriksen & Eriksen, 1974; Lavie, 1995; Yantis & Johnston, 1990).

As the two tasks here followed one another, the present findings provide support for our hypothesis that control of performance in selective attention tasks in accordance with current processing priorities depends on the availability of cognitive control mechanisms involved in coordinating alternating tasks. Indeed, as we discussed in the introduction to Experiment 4, control of task switching requires constant reconfiguration of processing priorities in accordance with the different subgoals and actions in the two tasks and is thus likely to load mechanisms for cognitive control of behavior in accordance with current processing priorities.

Experiment 5

In Experiment 5, we used a similar paradigm to Experiment 4 but with one critical difference: Memory set size was now reduced from six digits to one digit. We hypothesized that distractor effects would again be greater in the dual-task condition versus the single-task condition, because control of stimulus-processing priorities should still be loaded by the demand to alternate between the selective attention task and the memory task.

Method

Subjects. Ten new students from University College London participated in the experiment.

Stimuli, apparatus, and procedure. The apparatus and stimuli were the same as those used in Experiment 4. The procedure was the same as that used in Experiment 4, with one critical difference: The memory set size in the memory task now consisted of a single digit instead of six digits.

Results and Discussion

Memory task. The mean RT of the correct memory probe responses in the dual-task condition was 725 ms ($SD = 112$), and the mean error rate was 6% ($SD = 6\%$). These results are consistent with the typical range of RTs found in our previous experiments under conditions of low working memory load.

Selective attention task. Mean RTs and accuracy rates for the selective attention task were calculated for each subject as a function of the experimental factors and are presented in Table 8. A two-way within-subject ANOVA of distractor compatibility (incompatible vs. compatible) and task (single vs. dual) showed a main effect for distractor compatibility, $F(1, 9) = 29.99$, $MSE = 2,042$, $p < .001$, $\eta^2 = .769$, as well as a main effect for task, indicating a general dual-task cost in RTs, $F(1, 9) = 11.68$, $MSE = 3,566$, $p < .008$, $\eta^2 = .565$; see Table 8. More important, there was also a significant interaction between distractor compatibility and task, $F(1, 9) = 20.96$, $MSE = 80$, $p < .002$, $\eta^2 = .700$. As in Experiment 4, although distractor compatibility effects were significant in both the single-task condition, $t(9) = 4.42$, $SEM = 14.77$, $p < .01$, and the dual-task condition, $t(9) = 6.35$, $SEM = 14.36$, $p < .001$, they were significantly greater under dual-task conditions than under single-task conditions, as predicted. This difference in compatibility effects is unlikely to be the result of scaling due to the slower RTs in the dual-task condition, because the compatibility effect remained larger in the dual-task condition when calculated as a percentage of the overall RT per individual in each task condition. The distractor effect was 11% of the mean RT for the dual-task condition and 8% of the mean RT for the single-task condition, and this difference was significant, $t(9) = 3.96$, $SEM = 0.0073$, $p < .01$ (one-tailed). A similar two-way within-subject ANOVA of the error rates revealed a significant main effect of distractor compatibility, $F(1, 9) = 10.27$, $MSE = 0.002$, $p < .011$, $\eta^2 = .572$, but no main effect of task and no significant interaction between distractor compatibility and task ($p > .10$ for both).

Between-Experiments Analyses

Experiment 5 replicated the results of Experiment 4 and allowed us to generalize the effects of task switching on distractor interference in the selective attention task across the memory set size in the memory task. To further confirm this, we conducted three-way mixed ANOVAs on the RTs and error rates in the selective attention task of Experiments 5 and 6, with task (single, dual) and compatibility (incompatible, compatible) as within-subject factors and experiment (Experiment 4, Experiment 5) as a between-subjects factor. In these ANOVAs, there were no significant interactions with experiment ($F < 1$ in all RT results; $p > .10$ in all error results), thus confirming that the effect of task switching on the efficiency of distractor rejection in the selective attention task did not depend on the memory set size. Note also that the difference in distractor effects between the dual- and single-task condition was remarkably similar between Experiment 4 (27-ms difference) and Experiment 5 (28-ms difference). This was expected because no component of the memory task had to be carried across the selective attention task. However, the ANOVAs revealed a main effect for experiment in the RT analysis, $F(1, 18) = 8.54$, $MSE = 58,986$, $p < .01$, $\eta^2 = .310$. This main effect is somewhat surprising, as it indicates that the subjects in Experiment 4 (with high working memory load) were faster in the selective attention task than were the subjects in Experiment 5 (with low working memory load). However, as this main effect did not interact with task (or with any other factors, as we describe earlier) and these two experiments were run in different universities with different groups of subjects (Experiment 4 was run in Cambridge University, Experiment 5 was run in University College London), this main effect may simply be due to some general differences in the experimental situation or in the subject groups between these experiments.

In conclusion, although Experiments 1–3 demonstrated that the level of concurrent working memory load was important in determining distractibility, Experiments 4–5 confirmed that cognitive control of dual-task coordination also plays an important and independent role in selective attention.

General Discussion

The current work has addressed the relationship between cognitive control and selective attention in a novel way by considering the specific effects that different types of load have on the extent to which irrelevant distractors interfere with performance of a selective attention task. We have shown that whereas high perceptual load in the processing of task-relevant stimuli reduces distractor interference, high load on processes of cognitive control such as working memory and task coordination leads to increased distractor interference.

The contrast between the effects of perceptual load and cognitive control load on distractor interference clearly rules out general task difficulty as an alternative account for effects of either cognitive control load or perceptual load on distractor interference. Although both load manipulations increase general task difficulty, they clearly have opposite effects on distractor interference.

The dissociation between the effects of perceptual load and load in cognitive control on distractor interference provides support for our proposal that the efficiency of selective attention in rejecting irrelevant distractors depends critically on (at least) two dissociable mechanisms: (a) a rather passive perceptual selection mechanism that allows for distractor exclusion from early perceptual processes in situations of high perceptual load that naturally exhaust the available perceptual capacity in processing of the relevant stimuli and (b) a more active cognitive control mechanism that controls behavior in accordance with current priorities to minimize intrusion from irrelevant stimuli, even in situations in which the irrelevant stimuli were clearly perceived (as in situations of low perceptual load). This proposal presents a compelling

Table 8
Experiment 5: Mean Correct Reaction Times (in Milliseconds) and Error Rates on the Selective Attention Task as a Function of Task Condition and Distractor Compatibility

| | Distractor compatibility | | | | |
| | I | | C | | |
Task condition	M	SD	M	SD	I − C
Single					
M	804	128	741	115	63
%E	11	8	8	7	3
Dual					
M	881	140	790	133	91
%E	13	9	6	5	7

Note. I = incompatible; C = compatible; %E = error rate calculated as a percentage.

resolution to the long-standing early and late selection debate on the extent to which irrelevant distractors can be ignored, by combining both the early selection and late selection views within a hybrid model of selection.

Our proposed model also clarifies the relationship between selective attention and cognitive control. A few psychological theories have suggested that the allocation of attention may depend on processes of cognitive control (e.g., Baddeley, 1986; Duncan & Humphreys, 1989). However, as we discussed in the introduction, direct evidence for a specific causal role of cognitive control in selective attention has been sparse. Here we establish a direct causal role for cognitive control in determining distractor interference. Our findings thus make an important contribution to understanding the interplay between selective attention and cognitive control.

Frontal Cognitive Control and Selective Attention: Relating Load Theory to Neuropsychological and Neurophysiological Reports

Although it has long been speculated that cognitive control processes mediated by frontal cortices play an important role in selective attention (e.g., Desimone & Duncan, 1995; Posner & Petersen, 1990), there has not been much conclusive evidence for a causal role of such cognitive control processes in normal selective attention. Neuropsychological studies of patients with frontal lesions have established a general link between cognitive control processes mediated by frontal cortices and selective attention, as these frontal-lesion patients appear to experience deficits in both cognitive control and selective attention. They are often easily distracted and find it difficult to focus attention on goal-relevant stimuli rather than more salient but goal-irrelevant stimuli. In addition, they show deficits in planning, working memory, and coordination of multiple tasks (for reviews, see D'Esposito & Postle, 2000; Shallice & Burgess, 1996). It is possible and indeed tempting to interpret the deficits in selective attention that follow a frontal lesion as resulting from the additional deficits in cognitive control. For example, the increased distraction by goal-irrelevant stimuli may be the result of deterioration in the ability to control behavior in accordance with a temporary set of rules and priorities (e.g., Damasio, 1998; Miller & Cohen, 2001). However, it is hard to infer any direct causal role (e.g., for cognitive control in selective attention) merely from the co-occurrence of symptoms after a large anterior lesion.

More recently, electrophysiological single-unit recordings in monkeys demonstrated that prefrontal neurons not only respond selectively to visual stimuli in accordance with their task relevance but also can maintain this activity across intervening distractors presented during the delay period (in "delay match to sample" techniques; Miller et al., 1996; Rainer et al., 1998). These findings are consistent with the idea that such prefrontal neurons may be involved in control of selective attention by actively maintaining task-relevant information but again fall short of a causal demonstration at present.

Our psychological theory can accommodate these findings and relate such reports of neural activity to psychological function in a manner consistent with the current experimental results. As the cognitive control functions of working memory and dual-task coordination are typically associated with the same areas of pre-

frontal cortex reported in these studies (see Miller & Cohen, 2001), our findings suggest that these frontal cognitive control functions serve to control selective attention in accordance with task-relevant information by actively maintaining the current stimulus-processing priorities between relevant targets and irrelevant distractors. Indeed, our recent neuroimaging study showed that effects of working memory load in the prefrontal cortex interact with distractor-related activity in posterior visual cortices (De Fockert et al., 2001), as predicted from the psychological theory developed here. Moreover, the present findings that manipulations of load on working memory and on dual-task coordination consistently determine distractor interference effects allow us to establish a causal role for these cognitive control functions in the prevention of such distractor interference.

The Relationship Between Working Memory and Dual-Task Coordination in Control of Visual Selective Attention

Our series of experiments provides a clear demonstration that both working memory and processes of cognitive control that are involved in dual-task coordination play an important role in determining the efficiency of distractor rejection in visual selective attention tasks. Much recent evidence suggests that both dual-task coordination and active maintenance in working memory activate similar regions in the dorsolateral prefrontal cortex (Cohen et al., 1997; D'Esposito et al., 1995). This physiological association is in accordance with the functional link established in the present experiments between the cognitive control functions of working memory and of dual-task coordination in determining the extent to which observers are distracted by irrelevant stimuli.

Such a link is predicted from our proposal that successful performance in selective attention tasks that involve irrelevant but potentially competing distractors critically depends on cognitive control being available to ensure that task performance remains in accordance with current priorities. The cognitive functions of both working memory and control of task coordination are clearly involved in online monitoring of task performance in accordance with current priorities. Thus, loading either of these functions results in increased distraction from irrelevant low-priority stimuli.

In conclusion, the current work has highlighted the importance of considering the level and type of load involved in task-relevant processing as determinants of distractor processing and has demonstrated that the efficiency of selective attention can be accounted for in a load theory that involves both early perceptual selection mechanisms and late selection mechanisms of cognitive control. Such a hybrid model can resolve the long-standing controversy over the extent to which distractor processing can be prevented and suggests a clear role for cognitive control as well as perceptual load in determining the efficiency of selective attention.

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