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On the relationship between cognitive load and the efficiency of distractor rejection in visual search: The case of motion-form conjunctions

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ABSTRACT
Search for a target defined by a conjunction of movement and shape (moving X amongst moving Os and static Xs) is efficient, with static distractors contributing little to RT. How search is restricted to the moving items, whilst static items are ignored is not fully understood. Whether, passive bottom-up, or active top-down control processes are recruited is unknown. The current study addressed this question by asking participants to search for a motion–shape conjunction target under a low (one-digit) or high (six-digit) memory load. In Experiment 1, the number of distractors with target motion (moving Os), shape (static Xs), or neither (static O) was varied. RT was most sensitive to the number of moving items, less sensitive to the number of target-shaped items, and insensitive to the number of items without target features. A six-digit load slowed responding, but the effect of increasing distractor numerosity remained unchanged. Experiment 2 compared conjunction against feature (moving X amongst moving and static Os) search. Both searches were slowed by a high memory load but search slope remained unchanged. The results are consistent with the idea that sustained distractor rejection in motion–form conjunction search is largely insensitive to cognitive load.

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The visual world is complex and presents the visual system with much information and many possibilities for action. Selective attention is the suite of mechanisms that enable people to manage this complexity. The visual search task in which a target must be found amongst a varying number of distractors (see Chan & Hayward, 2013), provides a window on these mechanisms. Research using this task has demonstrated how observers are sensitive to basic visual features, such that targets defined by these features (e.g., colour, motion, size, or orientation) may be found easily and with little cost of increasing the number of items in the display (see Wolfe & Horowitz, 2004).

In addition to efficiently detecting a lone target defined by a single feature, feature information may be used to restrict search to a specific subset. Egeth et al. (1984) showed that when participants searched for a target amongst a colour-defined subset, increasing the number of elements outside this subset made no difference to performance, suggesting participants could use colour to restrict search to just this subset (see also Friedman-Hill & Wolfe, 1995). Motion may also be used to restrict the search to a subset of items; for example, McLeod et al. (1988) showed that when participants searched for a moving target amongst moving and static distractors, increasing the shape similarity between the target and static distractors did not impair performance, suggesting that the static items had been effectively filtered from the search. Interestingly, in the case of a search for a moving target amongst moving and static distractors, observers spontaneously limit the search to the moving elements. Von Muhlenen and Muller (2000) asked participants to find a moving X target amongst varying numbers of moving Os, static Xs, and static Os. The results showed that the number of moving Os had a large influence on performance with a much smaller influence of the static Xs and no influence at all of the static Os. These results are broadly consistent with a pre-eminent role for motion in controlling search, but one in which filtering by motion is not perfect, leaving some

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influence of non-moving items that have the target shape. Interestingly, items that have no target features had no effect on performance at all.

Von Muhlenen and Muller (2000) explain performance in this task in the following way. Drawing on the Attentional Engagement Theory of Duncan and Humphreys (1989) they suppose that target present decisions are made by matching the search stimuli against a target template that specifies the sought shape, but not its motion. When matches with the target template exceed a certain threshold a "target present" response is issued. To the extent that the stimuli are confusable with the target shape, they will activate the target template and compete for selection. Two factors then impact on this template matching process. First, motion is used to up-weight the moving stimuli over the static stimuli. The upshot of this process is that stimuli with no target features at all, do not match the target template and are not up-weighted by motion, thus they do not increase search times. Static items that do possess the target form do match the template but their influence is attenuated since they are not up-weighted according to their motion. Second, the representation of moving items is degraded, either due to noisy representation of their shape or noisy cross referencing between the motion and shape signals. The upshot of this is that the already up-weighted moving distractors are also more difficult to distinguish from the target during the template matching process, essentially reducing the signal-to-noise ratio, and increasing the chance of errors, meaning that a serial attentional mechanism may need to verify the target status of a selected item, before issuing a response, leading to increases in RT correlated with the number of moving items.

According to the account of Von Muhlenen and Muller (2000), the major distinction to be drawn is between the moving and static items; whilst the moving items are up-weighted according to their motion feature, the static items are unmodulated. Within the static items, those with the target form interfere slightly due to matching the form-based template; however, apart from this, each type of static distractor is treated similarly. However, there are good reasons to suspect that different types of static distractors may be treated differently, by distractor rejection mechanisms, with a greater incentive to eliminate the static items with the target form, since these items have the greatest potential to interfere with target detection. One possibility is that different non-moving distractors in this context may recruit different mechanisms of distractor rejection, with distractors that have the target shape requiring more active control, than those that do not.

One way in which this could play out is with regard to inhibition. Cave and Zimmerman (1997) investigated how distractor inhibition in a search task could vary according to target–distractor confusability. Participants searched for the letter F amongst a heterogeneous set of letter distractors, before responding to the presence of a suddenly appearing "probe-dot" on the screen. When the array could contain highly confusable distractors (P or E) responses to probe-dots on distractors were slowed relative to when such distractors could not appear. Cave and Zimmerman (1997) thus suggest that inhibitory attentional processes may be recruited in order to modulate target-distractor competition in the process of shape identification. A related result was obtained in a study examining multiple object tracking, Pylyshyn et al. (2008) asked participants to keep track of a number of targets, whilst ignoring a set of distractors. When a probe appeared on a distractor, responses were slower compared with probes appearing on the background, a result consistent with distractor inhibition. However, when the depth plane of the distractors was different from the target, evidence for inhibition disappeared, even though the probe itself appeared at the same depth as the distractor. Thus, it may be that distractors that are clearly distinguished from targets in terms of their features do not compete for and may be passively filtered from selection. In contrast, distractors that do share target features may need to be inhibited to facilitate target selection. Interestingly, Dent et al. (2012) showed that responses to probe-dots on static distractors during a motion–form conjunction search were slower than those to probe-dots on the background, a result consistent with inhibition of static distractors that possess the target form.

In general, the idea that competition between stimuli for representation by shape processing mechanisms determines the extent to which attention mechanisms are required to modulate this competition is consistent with the broader Biased Competition Theory of Attention (e.g., Desimone & Duncan, 1995). According to Biased Competition Theory, stimuli compete to control the responses of neurons that are tuned to their properties, when multiple stimuli are present the response to each is diminished, but this competition can be overcome by attentional cues that may serve to bias the competition in favour of one stimulus or another. In the context of the experiment of Von Muhlenen and Muller (2000) it may be possible to use motion to bias the competition in the form system specifically by inhibiting the representation of the highly interfering static items that share the target shape.

Relatedly, other recent theorizing in the domain of visual search emphasizes the importance of identifying and rapidly rejecting distractors before subsequent mechanisms attempt to identify the target. According to this approach, the first thing to do in a search is decide which elements are definitely not targets, before attempting to find the target amongst the remaining items. Buetti et al. (2016; see also Lleras et al., 2020) suggest an early stage of processing in a search: "screening". During screening, all items in the scene are analysed for their similarity to the target, with the output from this stage being a binary classification of 1 or 0. Items with some similarity to the target that are worthy of further scrutiny gain a value of 1 (termed "candidates"), and items that are sufficiently different to the target that they can be immediately rejected gain a value of 0 (termed "lures"). Only items with a value of 1 pass the screening stage and go on to receive further processing. Thus, here we have a model explicitly proposing two major stages of distractor rejection, an early screening process, and a later scrutiny processes. Applying the Buetti et al. account to the study of Von Muhlenen and Muller (2000), the rejection of distractors without target features (static Os) could be accomplished by screening, with only distractors with at least one feature being further scrutinized. Whilst it is useful to see how such a process of passive screening (perhaps implemented by the computation of a target-contrast signal, e.g., Lleras et al., 2020) could lead to efficient rejection of distractors without target features, without further mechanisms and assumptions this model does not accommodate the differential impact of moving and static distractors that do share one feature with the target. One possibility would be to allow feature-based guidance to intervene in order to reject the static distractors with the target form. Following motion-based inhibition, only moving elements will remain to compete for capacity-limited shape processing mechanisms to confirm target status.

The Load Theory of Attention developed by Lavie and colleagues (see Murphy et al., 2016, for a review) provides a useful framework within which to situate active and passive mechanisms that serve to determine the ways in which stimuli compete for perceptual processing. Essentially, the core of this theory is that the perceptual analysis of visual stimuli draws on limited resources (perceptual load), but these resources are always fully allocated to the stimuli present in perception. If task relevant stimuli fail to exhaust capacity, spare processing resources "spill over" to irrelevant stimuli, and this may create interference with the processing of relevant stimuli. Since under conditions of low perceptual load, task-irrelevant distractors are often perceptually analysed, domain general cognitive processes must be recruited to reject distractors at a later stage of processing (creating cognitive load). Evidence to support this theory comes from dual-task studies investigating the impact of a secondary cognitive load (usually in the form of a verbal memory load) on a primary task involving distractor rejection. Lavie et al. (2004) demonstrated that interference from a task-irrelevant flanker in the flanker task (Eriksen & Eriksen, 1974) was greater under a high compared with a low memory load, consistent with the idea that distractor rejection recruits domain-general cognitive processes. Other studies also demonstrate that the interference from a salient but task-irrelevant distractor can increase, when participants are given a high cognitive load in the form of a large concurrent memory load (Boot et al., 2005; Burnham, 2010; Lavie & de Fockert, 2005). These results are consistent with the suggestion that distractor rejection often recruits domain general resources.

Load theory has been successful at flexibly accounting for a range of data, however this success comes at a cost, and the theory has been criticized for its rather vague notion of perceptual load. In particular, it has been difficult to offer an a priori definition of what constitutes perceptual load, leading to the accusation that perceptual load is often defined circularly, with high perceptual load being associated with any manipulation that leads to reduced irrelevant distractor processing (Roper et al., 2013; Tsal & Benoni, 2010). One aspect of this debate has been the suggestion that when perceptual load manipulations depend on manipulating the presence of potentially relevant distractors these effects are really due to low level perceptual interference with the target or "dilution" (see Tsal & Benoni, 2010). However, more recently, the construct of perceptual load has been systematically related to independent measures of perceptual competition and perceptual similarity between targets and distractors. Torralbo and Beck (2008) explicitly related perceptual load to competition for representation in the form identification system, by showing that interference from an irrelevant distractor could be reduced when the relevant to be discriminated letters were presented further apart, or in different visual hemifields, factors known to influence competition in the visual system. Torralbo and Beck (2008) suggest that perceptual load can thus be understood in terms of competition for access to the receptive fields of neurons in the early and mid-levels of the visual system. Furthermore, under such conditions of perceptual load they suggest that top-down control is required to resolve this competition. In a similar vein, Roper et al. (2013) examined how the similarity between the target and distractor, and between multiple distractors, influenced both search efficiency (the increase in RT seen as display size is increased) and the extent of interference from an irrelevant flanker. Thus, according to Roper et al. (2013), how a particular distractor type affects search efficiency can be used as an a priori metric to quantify perceptual load.

Applying the framework of load theory to the task of Von Muhlenen and Muller (2000) on the whole as a conjunction search task (e.g., see Lavie & Cox, 1997), the task should be one in which the perceptual load is relatively high. However, the different types of distractors would be expected to contribute differentially to the perceptual load imposed by the task. In particular, distractors without target features (static Os) would be expected to impose little perceptual load, and accrue little in terms of perceptual processing resources, explaining why they contribute little to response time. Distractors with at least one target feature should draw on perceptual processing resources. However, additional mechanisms would be required to specify how these resources are distributed and how the search task is then resolved. One promising suggestion following Torralbo and Beck (2008) would be that competition within the form processing system is the primary limitation on performance here and that, in this case, top-down control mechanisms use the feature of motion to exclude stationary items with the target shape from these computations, leaving the form system to deal with the relatively easier task of discriminating between the shapes of the moving stimuli.

It is also interesting to consider the temporal relations between the potentially distinct distractor rejection mechanisms at play in the task of Von Muhlenen and Muller (2000). Recent work in the context of distractor rejection and cognitive control distinguishes between "proactive" and "reactive" processes (e.g., Geng, 2014; Braver, 2012), that differ according to the time at which they may be applied. Proactive control in this context refers to the advance specification of stimulus processing priorities, which serve to configure the system to prioritize relevant and deprioritize irrelevant stimuli, the target template discussed by Von Muhlenen and Muller (2000) would fall under this description. Reactive control here refers to a process that is initiated in response to unfolding stimulus processing; in particular, when stimulus processing results in conflict, mechanisms are subsequently deployed in order to resolve this conflict (see Braver, 2012). Applying this proactive vs. reactive framework to the task of Von Muhlenen and Muller (2000) then, configuring the target template, leading to the passive exclusion of distractors with no target features, would be an example of proactive control. However, subsequent reactive processes may then be required to suppress the static items that may conflict with the correct identification of the moving target, and the extent of the engagement of this process may be proportional to the degree of conflict with form processing, this would explain why the moving Os continue to influence performance since they may not be reactively suppressed in this way.

It is notable that the idea of reactive suppression has already been recruited to explain certain studies conducted within the load theory framework. Lavie and Fox (2000) investigated how perceptual load in this case implemented as a difference in relevant display size impacted on negative priming. Negative priming refers to the finding that responses are slowed when a current target played the role of distractor on the previous trial. Lavie and Fox (2000) showed that when a task irrelevant flanker on trial *n*–1 became the target on trial *n*, the extent of negative priming depended on the relevant perceptual load, being lower when the load was higher. The authors suggest that only under low load conditions are reactive suppression processes required to exclude irrelevant but mandatorily processed distractors. Similar reactive processes could very well be involved in resolving the competition from static X distractors in the paradigm of Von Muhlenen and Muller (2000).

Thus, it may be possible to identify at least three different mechanisms of distractor rejection contributing to efficient search for motion–form conjunctions: (1) passive screening, which may rely on proactive mechanisms specifying target properties; (2) motion-based inhibition, which may be deployed in proportion to the extent to which stimuli cause conflict and interference; and (3) rejection during form-based scrutiny of the moving items, likely after initial erroneous selection of distractors. The goal of the current investigation was to explore whether these putatively distinct processes of distractor rejection might place a differential draw on domain-general cognitive processes. To this end, the current study investigated if the success of rejecting different types of distractors in a visual search might be differentially sensitive to the imposition of a task irrelevant memory load.

A classic method used to investigate the load placed on domain-general cognitive resources by any psychological process, is to examine if that primary process is disrupted when general cognitive resources are diverted, often by asking the participant to hold memory loads of various sizes in mind. For example, Jonides (1981) investigated the selection of a target letter from an array of letter distractors. Participants were presented with a cue that indicated the likely location of the target. When the cue took the form of an arrow symbol, presented some distance from, but pointing to, a potential target location, the participants' ability to use this cue was impaired by a simultaneous memory load. In contrast, when the cue took the form of a stimulus appearing directly at a potential target location, participants use of that cue was unimpaired by a simultaneous memory load. These results are consistent with the use of a process of interpretation that translates the central symbolic arrow cue into the likely target location, a process that is sensitive to memory load.

As discussed above, more recent studies conducted within the load theory framework have demonstrated increased interference from a task-irrelevant flanker in the flanker task (Lavie et al., 2004) and increased interference from a salient but task-irrelevant distractor (Boot et al., 2005; Burnham, 2010; Lavie & de Fockert, 2005), when participants are given a high cognitive load in the form of a large concurrent memory load. These results are consistent with the suggestion that distractor rejection often recruits domain general resources.

There are, however, clear limits on the types of process that are disrupted by a simultaneous cognitive load. Logan (1976, 1978) investigated the influence of cognitive load on visual search, using a difficult search task for a target letter amongst distractor letters in which RT increased by about 60 ms per item (a level of efficiency indicative of inefficient serial processing of the display). The results consistently showed that whilst performance with a seven-digit memory load was reliably slower by up to 100 ms than performance without such a load, there was no change in search efficiency (the slope of the function relating RT to display size). Similar results have also been obtained more recently with a secondary visual load of coloured squares (Woodman et al., 2001). These results are consistent with the idea that the process of serially shifting attention through a set of similar items does not require the continued availability of general processing resources. However, such general resources may be required for other search processes including initiating search, by configuring the appropriate search goals, explaining the overall cost to RT.

Thus, whilst there is evidence of impaired rejection of salient distractors in some search tasks, distractor rejection in serial search tasks appears not to be similarly impaired. However, the reliance of a broader range of search processes, on domain-general cognitive resources, remains poorly understood. In particular, returning to the example of an efficient conjunction search for conjunctions of motion and shape, it is at least theoretically possible to delineate three types of distractor rejection process that may broadly correspond to three possible types of distractor: (1) passive screening, resulting in the rejection of distractors with no target features; (2) motion-based inhibition, which may suppress stationary items possessing the target shape; and (3) the type of more detailed processing of the remaining candidates akin to the type of form-based scrutiny studied by Logan (1976, 1978).

Unfortunately, relative to other visual dimensions such as colour or shape, how motion can be used to influence search is relatively understudied. In particular, the findings of Von Muhlenen and Muller (2000) have not since been revisited, and no previous study has investigated the influence of cognitive load on the guidance of search by motion. The goal of this study was to determine to what extent the distractor rejection processes, which lead to efficient search for conjunctions of motion and shape, are sensitive to cognitive load. In particular I was interested to discover if the influence of cognitive load might be a factor that would dissociate two processes of parallel distractor rejection – passive screening, which may not depend on domain general resources, and active inhibition, which may put a larger load on domain general cognitive resources. To this end in the current study, participants located a moving X target, amongst varying numbers of moving O, static X, and static O distractors. Following Logan (1976, 1978) the effect of increasing the number of each type of distractor and how this might interact with memory load (one or six digits) was measured. If the rejection of a particular distractor type recruits domain-general resources, the effect of increasing the numerosity of that distractor should be greater under conditions of memory load. Experiment 1 varied the number of each type of distractor in a display and examined how a high or low memory load would impact on the ability to ignore these items. Experiment 2 took a different approach and contrasted the search for a moving X in displays containing moving and static O distractors (feature search) with a search for a moving X in displays containing a mixture of moving Os and static Xs (conjunction search).

In the experiments reported here, the motion used took the form of a vertical oscillation. The original study of McLeod et al. (1988) used a form of translational motion whereby items "streamed" up the screen, disappearing at the top before wrapping around and reappearing at the bottom. Thus, the paths of motion used by McLeod et al. (1988) were longer, of only one direction and did not involve abrupt changes in direction. However, subsequent researchers have often preferred to use oscillating motion since it presents several advantages. Studies that have used oscillating motion (e.g., Treisman & Sato, 1990; Driver et al., 1992; Dent et al., 2011, 2012; Dent, 2014) have shown that oscillating motion is a cue that is highly effective for guiding search, and is comparable to translational motion in effectiveness. Using translational streaming motion requires careful arrangement of the stimuli, often into separate tracks in order to prevent collisions between stimuli. When stimuli move over long distances there are also large-scale changes in the locations of stimuli in addition to the presence of motion. In addition, wrapping stimuli around the screen when they reach the screen edge introduces shape distortions that are undesirable. Using oscillating motion overcomes these problems by holding constant the gross location of the stimuli, whilst varying the presence of motion. In order to avoid confusion and to maintain consistency with the prior literature, I will refer to the oscillating stimuli simply as "moving".

Experiment 1

Experiment 1 took the approach of factorially varying the numerosity of each of three types of distractor. Participants searched for a moving X target that was always present and was embedded in displays of different numbers of moving O, static X and static O distractors (four or eight of each). This approach is similar to that of Von Muhlenen and Muller (2000), although the current experiment did not make any attempt to balance the overall distribution of the shape and motion features in the displays, unlike Von Muhlenen and Muller. Following these earlier results, it was anticipated that in the low memory load condition, the number of moving O distractors would exert a significant effect on performance, with a smaller effect of the number of static Xs and a negligible effect of the number of static Os.

If it is the case, as suggested above, that a passive screening mechanism may be employed to exclude highly dissimilar distractors, whereas an active inhibitory process based on motion inhibition must intervene to exclude static X distractors, then these two processes may respond differently to the imposition of a memory load. It would be reasonable to expect the passive screening process to remain equally effective in the face of a high memory load. If the static X distractors remain equally well excluded regardless of memory load then a negligible effect of the number of static Os would be expected in both the low and the high memory load conditions. In contrast, if motion-based inhibition is a process that recruits domain-general cognitive resources, then it should be disrupted by a high supplementary memory load. The effect of varying the number of static Xs ought then to be greater in the high compared to the low memory load condition, as these items now compete for selection. How the effect of the number of moving Os might change with increasing memory load is somewhat more uncertain. If the number of moving Os already affects RT with a minimal memory load, it may be unlikely to increase further under a high memory load. This possibility of a null effect of memory load on the cost of increasing the number of competing moving O distractors, is underlined by previous null findings of memory load effects on search efficiency in tasks with non-zero search slopes (e.g., Logan, 1976, 1978). An alternative possibility is that if the static X distractors are no longer be excluded under a high memory load, this may alter the final form-based scrutiny phase of the search from a relatively simple feature search (moving X target amongst moving O distractors) back to a conjunction search (moving X target amongst moving O and static X distractors) and this may increase the influence of the number of moving Os under high load conditions, as each item requires more detailed processing.

In summary, both a passive screening process, and an active motion-based inhibition process may serve to reject distractors in motion-form conjunction search, paving the way for form-based scrutiny of the remaining items. If these processes impose differing loads on domain general cognitive processes, then then they should be differentially disrupted by the increased cognitive load of holding a larger list of digits in memory. The upshot would be an increased effect of increasing the number of static Xs, but not static Os, on performance. This would manifest as a significant interaction between the number of static Xs and memory load in the analysis.

In addition to the possible effects on search efficiency stemming from changed effects of increasing the number of different distractor types, overall increased response time in the high memory load condition is likely. This effect could occur due to the increased time required to configure the distractor rejection and other mental processes prior to commencing the search as suggested by Logan (1976, 1978). This effect would manifest as a main effect of memory load in the analysis.

Method

Participants

In Logan (1976), eight participants were tested, yielding a robust effect of memory load on performance. GPower (Erdfelder et al., 1996) estimated that 10 participants would be required to reliably (0.95 power) observe an effect of this magnitude ($\eta_p^2 = 0.67$), as a main effect in ANOVA. In the study of Von Muhlenen and Muller (2000), robust effects of varying the number of moving Os and static Xs were observed with six participants. For the current experiment, the sample size was set in advance at 20 participants, which should be adequate to detect the effects of both memory load and variations in the number of elements presented. The participants were undergraduate students from the University of Essex (13 females and seven males, aged between 18 and 23 years), who volunteered to take part.

Apparatus

The experiment was conducted using iMac computers. The experimental programs were written using MatLab (The MathWorks, Natick, MA) and the Psychophysics toolbox (Brainard, 1997) running under MacOS X.

Design

The experiment manipulated four within-participants factors, each with two levels, memory load (one or six digits), the number of moving Os (four or eight), the number of static Xs (four or eight), the number of static Os (four or eight). RT target localization accuracy, and memory accuracy were all recorded.

Stimuli

The stimuli were viewed from a distance of approximately 57 cm and all measurements of visual angle are based on this distance. The search displays were composed of the letters X and O, each drawn using white lines 0.5 mm (0.05 degrees) wide, and measuring 5 mm (0.5 degrees) at the widest point horizontally and vertically (see Figure 1 for an illustration). The displays were constructed by populating the cells of a grid of 121 or 11 × 11 locations, where each cell was 10 mm (1 degree) wide, such that the search letters were separated by at least 5 mm. All distractor types were equally distributed between the left and right halves of the display. Letters never appeared in the central column of the stimulus selection grid, leaving 110 possible locations. A fixation cross (5 mm × 5 mm or 0.5 × 0.5 degrees) was presented at the centre of the screen. Letters were either moving or static. Moving letters moved with a vertical oscillation (15 mm/sec or 1.5 degrees/sec) through 3 mm starting in an upward direction, and with all moving items moving in phase. The target was a moving X and was always present. The moving X target appeared on the left on 50% of trials and on the right on 50% of trials. A square frame (150 × 150 mm or 15 × 15 degrees) marked the boundaries of the display.

The digits for the memory load were drawn in the "Arial" font, size 24, (5 mm or 0.5 degrees high). The width of each letter varied, but the maximum width of a set of six letters was 32 mm (3.2 degrees).

Procedure

The experiment was conducted in a small testing booth under normal room lighting. Trials were presented in blocks of 128 composed of eight repetitions of each of the trial types created by combining the factors of memory load (one or six digits), the number of moving Os (four or eight), the number of static Xs (four or eight) and the number of static Os (four or eight), all trials were randomized. The experimenter gave verbal instructions before participants completed a block of practice trials. Following this, participants completed three blocks of trials (384 experimental trials, 24 trials per cell).

Each trial began with the presentation of the memory load in the centre of the screen for 1500 ms (see Figure 1 for an example), this was immediately replaced by the outline square frame and the fixation cross for 500 ms, before the search display appeared. The search display was exposed until the participant responded. Participants pressed the z key on the keyboard to indicate that the target appeared on the left and the m key on the keyboard to indicate that the target appeared on the right. The screen was then cleared and the participant recalled the memory load numbers. On trials with a memory load of one, participants typed a single number, on trials with a memory load of six, participants typed six numbers, and could not progress in the experiment until the required number of numbers had been typed. As the numbers were entered they appeared on the screen, participants were not permitted to change their responses once entered. Once the numbers had been provided, the next trial commenced. Participants were instructed that they could recall the numbers in any order, and to guess if they could not recall one of the numbers.

Results

Search performance

Search accuracy and RT were analysed using repeated-measures ANOVAs with the following factors: the number of moving Os (four or eight), the number of static Xs (four or eight), the number of static Os (four or eight), and memory load (one or six digits). Regarding accuracy, performance was overall highly accurate at 99% see Table 1 for a breakdown. There were no significant main effects or interactions in the accuracy analysis, Fs < 3.49, $\eta_p^2 > .15$, $p > 0.076$.

Regarding RT, incorrect responses (0.6%) and responses equal to or greater than 4000 ms (a further 1%) were excluded from analysis. Analyses were conducted both regardless of memory task accuracy and when the 5.7% of trials where participants incorrectly reported the single digit in the memory load 1 condition, or incorrectly reported two or more numbers in the memory load 6 condition were excluded. There were no differences in the statistical significance of any of the effects or interactions between these two analyses. Below, the more informative analysis where inaccurate trials were removed is reported. Figure 2 illustrates the main effects of each of the variables in the design. The main effect of moving Os was significant $F(1,19) = 113.52$, $\eta_p^2 = 0.86$, $p < 0.0001$, with an increase of 34 ms/item. The main effect of static Xs was also significant $F(1,19) = 12.22$, $\eta_p^2 = 0.39$, $p < 0.005$; however, in comparison with the effect of the number of moving Os, it was much smaller at 11 ms/item (a difference that was statistically reliable when tested separately $F(1,19) = 53.96$, $\eta_p^2 = 0.74$, $p < 0.0001$). The main effect of the number of static Os was not significant $F(1,19) = 0.8$, $\eta_p^2 = 0.04$, $p = 0.38$ (−2.7 ms/item). The main effect of memory load was significant $F(1,19) = 16.31$, $\eta_p^2 = 0.46$, $p < 0.001$, with participants 202 ms slower to respond with a six digit load.

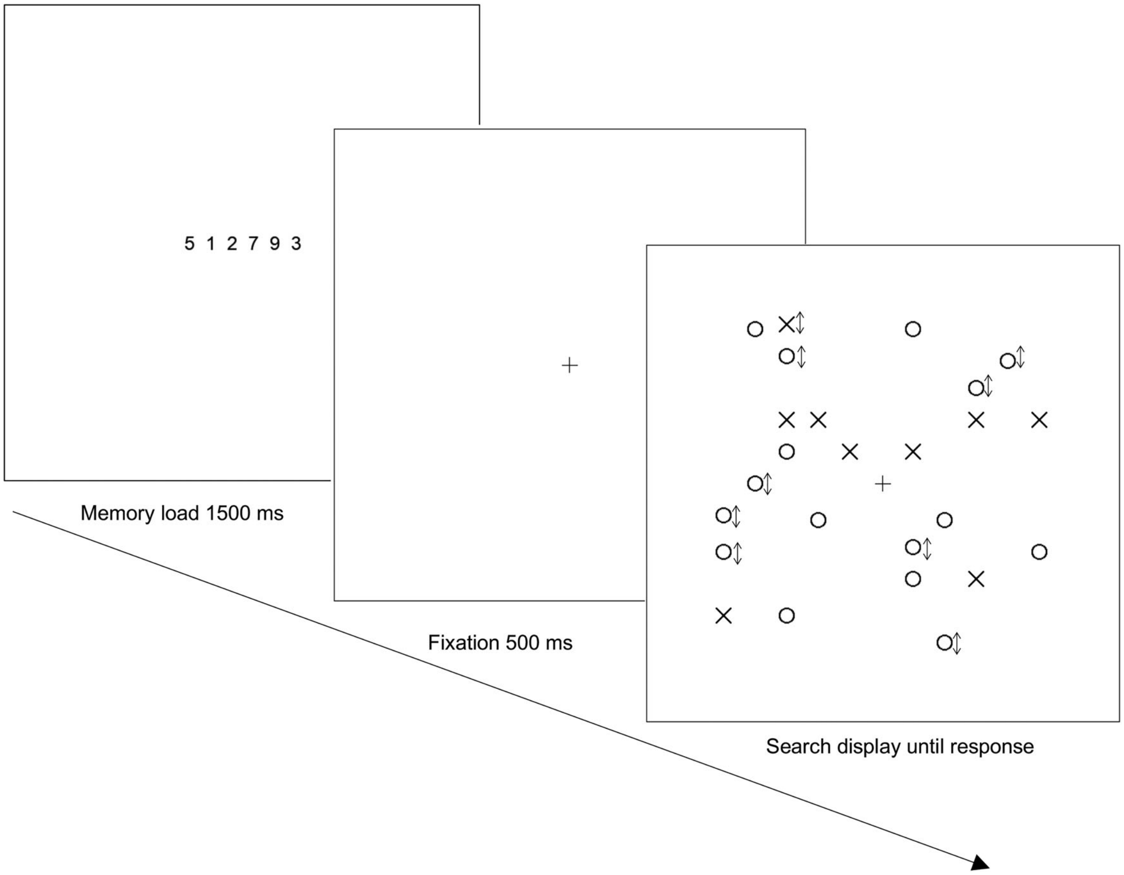

Figure 1. Illustration of the experimental paradigm in Experiment 1. The large arrow represents the passage of time. The final frame illustrates the search display, with small arrows indicating the movement of the search elements. The target is present in the upper left, there are eight static Xs, and eight static Os, and eight moving Os.

Importantly, load did not change the effect of increasing the number of any of the distractors on RT, the interactions between load and the number of moving Os, static Xs and static Os were all non-significant Fs < 1. No other interactions were significant Fs < 1.93, $\eta_p^2 < 0.19$, ps > 0.09. The detailed values for all these tests are presented in Table 2 for the interested reader.

Bayesian analyses were conducted using JASP (Version 0.14.1; JASP Team, 2021) in order to quantify the evidence in favour of the critical null interactions between the number of each type of distractor and memory load. The analysis was in agreement with the frequentist ANOVA presented above in that the data were best explained by a model including only the effects of memory load, moving Os and static Xs, but excluding any other experimental effects or interactions, $BF_{10} = 7.9 \times 10^{31}$, indicating decisive support for this model over a model including only the effect of the participant. Considering the interaction between memory load and the number of static Xs, $BF_{01} = 5.171$, indicating substantial support for a null interaction (the interaction is around five times more likely to be null than otherwise). Similarly, considering the interaction between memory load and the number of moving Os, $BF_{01} = 6.328$, indicating substantial support for a null interaction (the interaction was more than six times more likely to be null than otherwise). Finally, considering the interaction between memory load and the number of static Os, $BF_{01} = 3.475 \times 10^{12}$ indicating decisive support for a null interaction (the interaction was overwhelmingly more likely to be null than otherwise).

Memory performance

Accuracy was analysed using repeated-measures ANOVA as above (see Table 3 for a breakdown). Responses were scored without regard to the position of the number within the response. A score of 1 was

Table 1. Search accuracy Experiment 1.

Static Xs	4				8			
Static Os	4		8		4		8	
Moving Os	4	8	4	8	4	8	4	8
Memory load 1	0.992	0.998	0.998	0.996	0.994	0.996	0.990	0.996
Memory load 6	0.996	0.994	0.994	0.998	0.994	0.994	0.992	0.988

given for each recalled number that was present in the initial string. If a correct number was entered more than once only the first instance was considered. The recall scores in the case of six item trials were converted to proportion by dividing by six. The main effect of memory load $F(1,19) = 13.34$, $\eta_p^2 = 0.41$, $p < 0.005$, was significant. Participants were slightly less accurate with six items than one item, 0.99 vs. 0.93 for one and six items respectively translating into memory for 0.99 or 5.6 items. No other effects or interactions were significant Fs < 3.34, $\eta_p^2 < 0.15$, ps > 0.083.

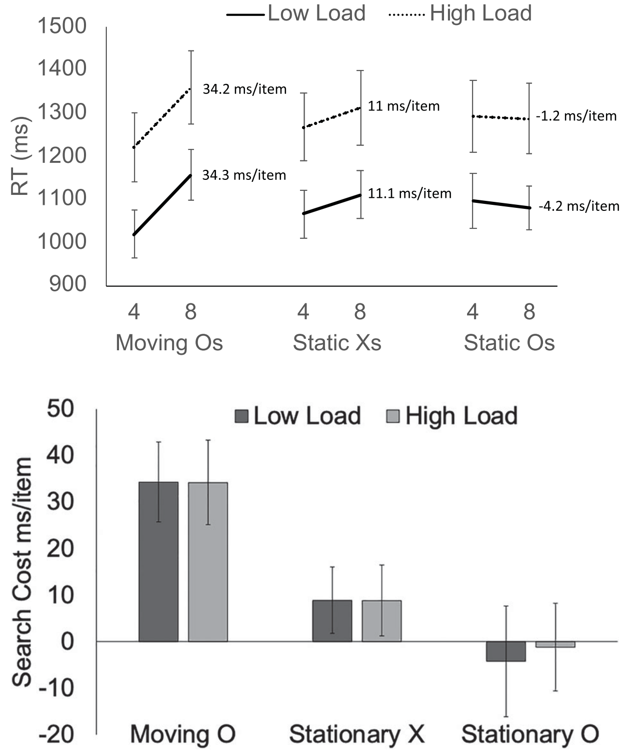

Figure 2. The upper panel illustrates overall RT as a function of the number of distractors, the left panel shows the effect of the number of moving Os, the middle panel the number of static Xs and the right panel the number of static Os. Error bars show standard errors of the mean. Solid lines show data for trials with low (one item) memory load and dashed lines show data for trials with high (six item) memory loads. The lower panel illustrates the cost to overall RT of increasing each distractor type under each memory load.

Discussion

The results showed that whilst participants were not perfect in retaining six digits they were able to reliably retain 5.6 digits in the high load condition. In the low load condition, participants retained one item nearly perfectly (0.99 items on average). The manipulation of cognitive load was therefore effective. In addition to being presented with more items, participants demonstrably held a greater number of items in memory in the high than in the low load condition. Holding a larger digit load in memory impacted search performance, increasing overall RT by 202 ms, although rather impressively this was not accompanied by an increase in errors, with the search remaining highly accurate. Thus, increasing cognitive load had a robust effect on performance. However, the manipulations of distractor numerosity did not interact with memory load, suggesting that the distractor rejection processes did not require continued access to domain-general cognitive resources. In the introduction, I highlighted a distinction between two primary mechanisms for large-scale parallel distractor rejection, passive screening and active inhibition. The current data were broadly consistent with the *existence* of these two processes since the two types of non-moving distractors exerted a differential influence on overall RT, only static items with the target shape exerted a significant cost, consistent

Table 2. ANOVA main effects and interactions for the Experiment 1 RT analysis including only accurate trials.

	Including only trials with accurate recall		
ANOVA term	F (1,19)	*p* value	η_p^2
Load	16.31	0.001	0.46
Static X	12.22	0.002	0.39
Static O	0.8	0.38	0.04
Moving O	113.52	<0.0001	0.86
Load × Static X	0.0001	0.99	<0.0001
Load × Static O	0.17	0.69	0.009
Load × Moving O	0.001	0.98	<0.0001
Load × Static X × Static O	0.66	0.43	0.03
Load × Static X × Moving O	0.51	0.49	0.03
Load × Static O × Moving O	1.92	0.18	0.09
Load × Static X × Static O × Moving O	0.64	0.43	0.03

Table 3. Memory accuracy Experiment 1.

Static Xs	4				8			
Static Os	4		8		4		8	
Moving Os	4	8	4	8	4	8	4	8
Memory load 1	0.983	0.988	0.992	0.985	0.990	0.992	0.983	0.979
Memory load 6	0.931	0.931	0.928	0.936	0.932	0.935	0.928	0.934

with much easier passive screening of items with no target features, and more difficult rejection of items similar in shape to the target. However, the results were inconsistent with the further proposal that these two forms of distractor rejection process may be distinguished in terms of their sensitivity to a supplementary memory load. The influence of neither type of distractor was sensitive to memory load. In particular, the cost associated with increasing the number of static Xs on the screen remained constant despite increased memory load, suggesting that the static Xs did not require general cognitive resources for their motion-based rejection. Thus, while the results may be consistent with different processes operating to reject different distractor types, they are inconsistent with the idea that these processes make any differential draw on domain-general cognitive resources.

One criticism of the approach taken in Experiment 1 is that it employs a non-standard conjunction search task, which does not measure search efficiency in the way typical in this literature. By independently manipulating the number of each type of distractor, displays will frequently contain unbalanced numbers of each type of distractor and this could impact performance (e.g., Sobel & Cave, 2002). In particular, since there were two types of static distractor, but only one type of moving distractor, on many trials the static distractors would form a substantial majority, with moving items forming a minority. Previous research (e.g., Sobel & Cave, 2002; see also Poisson & Wilkinson, 1992; Zohary & Hochstein, 1989) has demonstrated an advantage for processing items that have a minority feature. Minority features may have an advantage since items with minority features are likely to have greater bottom-up salience in the display (e.g., Itti & Koch, 2000). The imbalance in distractor numerosity could, by increasing the salience of moving items, undermine the use of top-down inhibition in these displays.

Performance in the conjunction task of Experiment 1 is not compared with a baseline feature search task employing the same features. This is because the design of Experiment 1 directly compared the effect of increasing each type of distractor. However, even though in Experiment 1 increasing memory load may not increase the impact of increasing the number of distractors, it may be that a motion-form conjunction search shows larger general effects of memory load compared with a feature search condition.

These criticisms were addressed in Experiment 2 which took a more standard approach and compared a conjunction search task (find a moving X target amongst equal numbers of moving O and static X distractors) with a form-based feature search task (find a moving X target amongst equal numbers of moving O and static O distractors). Note that in the form-based feature search task, the target is defined by its unique form, but differences in motion amongst the elements are present in order to match the conjunction search task. It was particularly important to include a feature-search baseline in Experiment 2, since distractors with no target features hypothetically permitting passive screening were not included in the conjunction search task. In this case, a feature search baseline provides a useful comparison with the conjunction condition since the form-based feature search is unlikely to recruit an active motion-based distractor rejection process in the same way as a conjunction search. Consistent with this, Dent et al. (2012) showed that whilst probe-dot detection times were slower when presented on static X distractors in a conjunction search, this same slowing did not apply in the case of a feature search task (find a moving X target amongst moving O distractors). How, will the effect of memory load impact these two tasks, and will a conjunction search show reduced search efficiency in the presence of a high memory load?

Experiment 2

Experiment 2 compared a motion-form conjunction search task, with equal numbers of two types of distractor (moving X target amongst moving O and static X), against a feature search task with one type of distractor (moving X target amongst moving O distractors). Static O items were omitted from the conjunction search displays and the numerosity of both remaining distractor types was increased in step. Implementing the conjunction search task in this way meant that the numerosity of each type of feature in the displays was always approximately equal, such that the often substantial minority and majority features present in Experiment 1 were avoided. If the use of active motion-based distractor rejection processes in Experiment 1 was mitigated by the frequent presence of a minority of moving items, accompanied by increased bottom-up salience, these processes should be re-engaged in Experiment 2. If active motion-based inhibition processes are indeed re-engaged in the conjunction task of Experiment 2, and if these processes draw on domain-general cognitive resources, then increased memory load would now be predicted to increase the effect of display size, as distractors re-compete for selection. In contrast, on the assumption that the involvement of inhibitory processes in a form-based feature search is either greatly reduced or even absent (see Dent et al., 2012), there should be no change in the efficiency of a feature search under a memory load. Note that the comparison between a feature search and a conjunction search is particularly informative in Experiment 2 since the conjunction search task no longer includes passively screened static O items for comparison.

Method

Participants

Given the robust memory load effect observed in Experiment 1, it was deemed acceptable to reduce the sample size to 16. The participants were undergraduate students from the University of Essex (12 females and four males, aged between 18 and 24 years), who took part in exchange for course credit.

Apparatus

The apparatus was as for Experiment 1.

Design

The experiment manipulated three within-participants factors, each with two levels, memory load (one or six digits), display size (nine or 17 items), and search type (feature or conjunction). RT and accuracy of target location responses, and memory accuracy were recorded.

Stimuli and procedure

The stimuli and procedure were as for Experiment 1 with the following exceptions. Participants performed two search tasks (feature and conjunction search) that were presented in separate blocks of trials. Participants completed four blocks of trials (two blocks of each task in alternating order, e.g., feature, conjunction, feature, conjunction), with the task presented first counterbalanced over participants.

In both tasks, participants were presented with either eight or 16 distractors, equally distributed over the left and right halves of the screen. The distractors were always accompanied by a single moving X target, which occurred equally often on the left or the right of the centre of the screen. In the feature search task, the distractors took the form of moving O, and static O distractors, whereas in the conjunction search task the distractors were moving Os and static Xs. The two types of distractors were always present in equal numbers (four or eight of each, with each type distributed equally over the left and right halves of the screen) such that participants viewed displays containing a total of eight or 16 distractors, accompanied by a single target. The task was to indicate whether the moving X target appeared on the left or the right of the centre of the screen.

As for Experiment 1, at the start of each trial participants were presented with a memory load of one or six digits to be retained and recalled at the end of each trial by typing the numbers on the keyboard.

Each block was composed of 64, 16 trials for each combination of memory load (one or six digits) and display size (nine or 17 items), yielding 32 trials per cell of the design in total. Within each block, trials defined by each combination of memory load and display size were presented in a random order.

Results

Search performance

Search accuracy and RT were analysed using repeated-measures ANOVAs with the following factors: display size (nine or 17 items), search task (feature search or conjunction search), and memory load (one or six digits). Regarding accuracy, performance was overall highly accurate at 99% see Table 4 for a breakdown. The effect of the search task was significant, with slightly poorer performance with conjunction than with feature search F(1, 15) = 6, $\eta_p^2 = 0.286$, $p < 0.05$, no other main effects or interactions were significant Fs < 3.55, $\eta_p^2 < 0.191$, $p > 0.079$.

Regarding RT, incorrect responses (1%) were excluded from analysis. Analyses were conducted both regardless of memory task accuracy and when the 3.4% of trials where participants incorrectly reported the single digit in the memory load 1 condition, or incorrectly reported two or more numbers in the memory load 6 condition were excluded. There were no differences in the statistical significance of any of the effects or interactions between these two analyses. Below, the more informative analysis with the inaccurate trials excluded is reported. Figure 3 illustrates the main effects of each of the variables in the design. The main effect of display size was significant F(1,15) = 56.98, $\eta_p^2 = 0.79$, $p < 0.0001$. The main effect of memory load was significant F(1,15) = 18.62, $\eta_p^2 = 0.55$, $p < 0.001$, with participants around 113 ms slower to respond with a six digit load. The main effect of the search task was significant F(1,15) = 137.73, $\eta_p^2 = 0.9$, $p < 0.0001$. However, the interaction between task and load was not significant F(1,15) = 1.26, $\eta_p^2 = 0.08$, $p = 0.28$, suggesting equal increases in RT as a function of memory load in both tasks. The search task and display size interacted F(1,15) = 98.88, $\eta_p^2 = 0.87$, $p < 0.0001$, such that the effect of display size was much larger (28 ms/item) for conjunction than for feature search (2 ms/item). However, memory load did not qualify the effect of increasing display size; the interactions involving load and the display size were all non-significant: memory load × display size F(1,15) = 0.1, $\eta_p^2 = 0.0006$, $p = 0.76$; memory load × search task × display size, F(1,15) = 0.11, $\eta_p^2 = 0.007$, $p = 0.74$.

Separate analyses were conducted on each task in order to explore the critical interaction between display size and load. In the conjunction search task the interaction between display size and memory load was non-significant F < 1, $p = 095$. Bayesian analysis using JASP (Version 0.14.1; JASP Team, 2021) revealed that the best model was one including the main effects of load and display size, this model was overwhelmingly more likely than the model with only participant as a term, $BF_{10} = 9.273 \times 10^7$. Regarding the display size × load interaction, $BF_{01} = 3.229$, indicating that the model with only the main effects was three times more likely that a model with the main effects and the interaction. In the feature search task the interaction between display size and memory load was non-significant F < 1, $p = 0.519$. Bayesian analysis using JASP revealed that the data were best explained by a model including only the main effect of load, excluding any other experimental effects or interactions, $BF_{10} = 5.708 \times 10^7$, indicating decisive support for this model over a model including only the effect of participant. Regarding the display size × load interaction, $BF_{01} = 8.453$, indicating substantial support for a null interaction (the interaction was eight times more likely to be null than otherwise).

Table 4. Search accuracy Experiment 2

Memory load	Low load		High load	
Display Size	9 items	17 items	9 items	17 items
Conjunction	0.992	0.975	0.988	0.988
Feature	0.988	0.996	0.994	0.996

Memory performance

Accuracy was analysed using repeated-measures ANOVA as above (see Table 5 for a breakdown). Responses were scored without regard to the position of the number within the response. A score of 1 was given for each recalled number that was present in the initial string. If a correct number was entered more than once only the first instance was considered. The recall scores in the case of six-item trials were converted to proportion by dividing by six. The main effect of memory load approached but did not reach significance F(1,15) = 4.086, $\eta_p^2 = 0.214$, $p = 0.061$. No other effects or interactions were significant Fs < 1, $\eta_p^2 < 0.038$, $p > 0.453$.

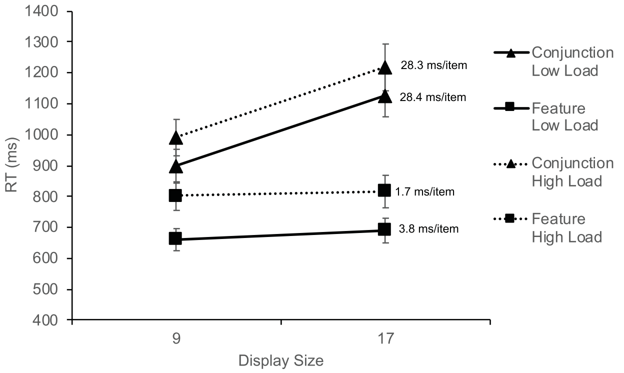

Figure 3. Search RT as a function of search task, memory load, and display size in Experiment 2. Conjunction search task is plotted with triangles, feature search with squares, high memory load with dotted lines, and low memory load with solid lines. Display size on the *X*-axis. Error bars show standard error of the mean.

Discussion

In Experiment 2 (E2), performance was again highly accurate with participants retaining an average of 5.75 digits in memory in the high load condition, suggesting that working memory was indeed loaded. Regarding the effects of load on the search task, the results of Experiment 2 were qualitatively similar to those of Experiment 1 (E1). Here, the two tasks differed markedly in both overall RT and search efficiency, with the conjunction search task slower and less efficient than the feature search task. Both tasks showed an overall cost to performance in terms of RT as a function of increased memory load, which was similar in size (around 100 ms). In addition, neither task showed any reduced efficiency as measured by search slope as a function of memory load. Estimating equivalent efficiency scores in E1 gives a value of 21 ms/item, which is close to the values of 28 ms/item observed in E2, this is consistent with similar efficiency in both experiments. The value of 28 ms per item observed here is a little larger than that typically observed in the motion-form conjunction search. This reduced efficiency likely stems from our adoption of a localization task, which does not permit early termination of the search by erroneously responding absent on target-present trials, and may rely on more precise spatial co-localization of feature information than is typical of present–absent search tasks. In summary, the results of Experiment 2 show that increasing memory load increases RT in a search task without changing efficiency, and the size of this increase is no greater in conjunction than in feature search. Thus, the distractor exclusion processes that are required to execute the conjunction search task do not seem to be particularly reliant on cognitive resources coextensive with working memory.

Of interest, the size of the cost on performance from increasing memory load in Experiment 1 was larger than in Experiment 2, exactly why this should be the case in not clear, although we note that the accuracy was also slightly higher with six digits in Experiment 2 than Experiment 1, indicating that participants in Experiment 1 may have experienced a larger cognitive load than those in Experiment 2. However, the important point is that within the same group of participants increasing memory load did not change the effect of display size.

Table 5. Memory accuracy Experiment 2.

Memory load	Low load		High load	
Display Size	9 items	17 items	9 items	17 items
Conjunction	0.990	0.982	0.959	0.958
Feature	0.984	0.984	0.957	0.958

General discussion

The results of the two experiments showed that holding a larger memory load impacted on the search, increasing overall RT by 100–200 ms, although rather impressively this was not accompanied by an increase in errors, with the search remaining highly accurate. Thus, increasing cognitive load had an effect on disrupting search performance. However, the manipulations of distractor numerosity in Experiment 1 did not interact with memory load, suggesting that the distractor rejection processes did not require continued access to domain general cognitive resources. Had this been the case, it would be expected that under conditions of high memory load the implicated distractors should begin to interfere with search performance and the extent of this interference should be proportional to distractor numerosity, with a greater number of distractors leading to greater levels of interference. Likewise, in Experiment 2, search efficiency remained unchanged despite increased memory load, and conjunction and feature search showed similar overall increases in RT.

In the introduction we highlighted a distinction between two hypothetical mechanisms for large-scale parallel distractor rejection, a passive screening process that may be related to proactive cognitive control, and active inhibition, a process that may be reactive in response to interference with stimulus identification. The current data were broadly consistent with the existence of these two processes since in Experiment 1 the two types of non-moving distractors exerted a differential influence on overall RT, only static items with the target shape exerted a cost, consistent with much easier passive screening of items with no target features. However, it was not the case that the influence of either of these types of distractor was sensitive to memory load. Likewise, in Experiment 2, changing the static O distractors of the feature search condition for the static X distractors in the conjunction search condition, did result in a slower and less efficient search; however, the effect of increasing memory load was the same in both conditions, increasing overall RT by around 100 ms without changing search efficiency. Thus, in two experiments, the cost associated with increasing the number of static Xs present on the screen remained constant despite increased memory load, suggesting that the static Xs did not require continuous access to general cognitive resources for their motion-based inhibition.

Previous research (Dent et al., 2010) demonstrated a deficit in the search for conjunctions of motion and form in patients with damage to the posterior parietal lobe, even though structures involved in the perceptual processing of motion were demonstrably intact (in one case). The exact mechanism behind this selective deficit is not known; the current results argue against a domain-general deficit in top-down control in these patients. Healthy observers holding a high memory load in mind certainly did not perform like patients with damage to the parietal cortex. The deficit observed by Dent et al. (2010) likely stems from compromised domain-*specific* processes.

Whilst one possibility is that different processes are responsible for rejecting the two different types of static distractors used in Experiment 1, but that they do not respond differently to the memory load manipulation, another is that, in fact, these two types of distractor are treated fundamentally similarly. Following Von Muhlenen and Muller (2000) the differential influence of each type of distractor could stem from asymmetrical weighting or guidance by motion and by shape. Adopting the activation map of Guided Search (e.g., Wolfe, 1994, 2021) both moving items and Xs would be more strongly activated than static items and Os, but the strength of this activation would much more strongly distinguish moving and static items, than items of different shape. Exactly why shape cues on this model would be less powerful than motion is not clear, especially given that the results of Experiment 2 show that the detection a single item differing in shape from the background is highly efficient. One possibility as suggested by Von Muhlenen and Muller is that the perceptual quality of the moving items is degraded due to smearing on the retina and other low-level factors. However, the data of Experiment 2 showing highly efficient feature search in similar moving displays would argue against this possibility. An alternative possibility for the dominance of motion over shape in this case is that as suggested by Von Muhlenen and Muller – a shape-based template is used to determine responses in this task, increasing the activation of the Xs may lead to too much interference with this process from the static Xs, and participants may therefore minimize the use of shape to guide the search in this context.

The idea of multiple representation of target features that serve distinct roles in search echoes the most recent iteration of the Guided Search model, version 6.0 (Wolfe, 2021). Guided Search 6.0 includes a guiding template representation that serves to increase the activation of locations with target-relevant features, but also a target template residing most usually in visual long-term memory that serves to govern the decision about whether a target is present. According to Guided Search 6.0, multiple items are currently selected and matched against the target template at any one time. Applied to the current data, motion would serve as the primary guiding representation with a secondary role for shape. However, the *target* template would be specified in terms of shape. A primary role for shape in specifying the target template in this case is likely since shape is primary for object identification, whereas typically object identification would be invariant with regard to motion. The process of matching items selected from amongst the display for form-based identification would be more efficient if other non-target items with the target shape can be excluded, and not applying form-based guidance in this context would serve that goal. On this account there is no requirement for an additional process of motion-based inhibition, on top of the influence of the target and guiding templates the results simply fall out of the assumption that motion and form features are used differentially to define each type of template.

According to one reading of the model put forward by Von Muhlenen and Muller (2000) the display size effects can be understood as stemming partly from a parallel competitive process whereby stimuli compete for a limited supply of activation that becomes more thinly spread as more items are added to the display, making the target less salient, or less efficiently processed. In the context of

Guided Search, this could be implemented by making the supply of activation for the activation map limited. However, the cost of increasing the number of moving Os and static Xs can also be understood in terms of the likelihood that distractors are erroneously selected for comparison against the target template. According to such an account, the time cost for increasing each distractor type is driven by the probability that it is erroneously selected by spatial attention. Moving items are most highly weighted and thus most likely to be erroneously selected followed by static X items, and then static Os. According to this account, it is not that different types of distractors present a different perceptual load to the system (e.g., Lavie & Cox, 1997) or consume different amounts of weight or other limited resources, rather different distractors differentially attract a single spatial focus of attention. A similar "slippage theory" has been used to account for other apparent demonstrations of parallel limited capacity processing in vision (e.g., Lachter et al., 2004), in particular Gaspelin et al. (2014) demonstrated how, when such slippage was eliminated, evidence for processing of a task-irrelevant distractor under conditions of low perceptual load in the flanker task was also eliminated. The pattern of current data can thus be explained most straightforwardly by suggesting that different types of distractors are differentially likely to attract deployments of spatial selective attention for selection and matching against a form-based target template.

However, one problem for a slippage account of the current data is that several previous studies have found increased distractor interference under conditions of high memory load (see de Fockert, 2013). Typically, the influence of a single salient distractor is greater under conditions of high cognitive load. If the disruptive influence of a salient distractor in search is understood in terms of the slippage or capture of spatial attention, then it becomes difficult to explain why slippage to a single salient distractor should be load sensitive, but should be load insensitive in the context of the current task. One possibility is that working memory load may specifically modulate the regulation or suppression of salience signals. Recent work suggests that under conditions where the interference from a salient singleton is reduced (e.g., display heterogeneity, distractor familiarity) reduced distraction is often accompanied by spatially specific inhibition at the location of the salient distractor (see Gaspelin & Luck, 2018). Likewise, previous research by Dent et al. (2012) demonstrated that static X distractors in the conjunction search are associated with spatially specific inhibition in a probe-dot paradigm. The current results are thus consistent with the idea that the load-sensitive processes responsible for the suppression of a single salient distractor may differ from the load independent processes that are responsible for the suppression of subsets of moving objects.

One possibility here is that inhibition of distractors in conjunction search recruits feature-based suppression mechanisms that operate prior to the computation of domain general salience signals at the level of a feature independent salience map (e.g., see Treisman & Sato, 1990). In contrast, reduction of interference from a single salient singleton may recruit processes operating directly at the level of a domain general salience map (e.g., Itti & Koch, 2000). At a more general level, the contrast between the failure to observe increased distractor costs in the current article and increased costs in prior work may suggest that the mechanisms for regulating salience (in singleton capture) may be different from more general guidance processes involved in conjunction search (e.g., Wolfe et al., 2010).

It should be acknowledged that there are many different ways to impose a memory load on participants, and still further methods by which a more general cognitive load can be imposed. Here, we used a simple task of retaining in memory a set of digits with no requirement to maintain the order of the digits and no requirement to rehearse the digits. This choice of task was based on the task used by Lavie et al. (2004). However, other studies have used different tasks, for example Lavie and de Fockert (2005; see also de Fockert et al., 2001) used a digit memory task in which the order of the items had to be retained. Other studies have imposed a cognitive load by requiring participants to engage in more active executive processing. Han and Kim (2004) demonstrated that in a difficult inefficient search task for a target shape, simply holding a set of digits or letters in memory did not further increase search slopes. However, in contrast, either reordering a set of letters into alphabetical order, or counting backwards in 3s, caused search slopes to approximately double. Burnham et al. (2014) compared the effects of visual, spatial, phonological and executive load tasks on visual search. Of particular relevance to the current study, the results showed that merely holding in memory the phonological properties of a set of stimuli (e.g., gah, gee, goo) was not adequate to disrupt search efficiency, whereas the executive task of backward counting was. Thus, it remains entirely possible that if a sufficiently difficult task was used that emphasized executive processes, such as backward counting, less effective filtering by motion would be observed.

In addition, an important consideration in evaluating the effect of a high cognitive load on performance is the appropriate baseline for comparison. In the current study, both the high and low load conditions involved a dual task memory load and differed only in the number of digits to be held. In other studies (e.g., Burnham et al., 2014; Lavie & de Fockert, 2005) the high cognitive load condition is the only dual task situation and this is compared against a single task low load baseline. The current study used dual tasks in both the high and low load conditions to equate any general dual task cost between the conditions. However, it may be the case that this approach hides a dual task search impairment that would be revealed if a single task baseline was employed. Further research will be needed to determine if a dual task cognitive load impairment can be observed with different tasks and baselines. Whilst we did not observe an increased cost of increasing distractor numerosity as a function of load, essentially search efficiency remained unchanged, we did observe an overall slowing of search response times. This overall cost to performance must be accounted for. Most models of search include a serial element, where stimuli are selected, either for identification (e.g., Guided Search, Wolfe, 2021) or for response selection (e.g., Attentional Engagement Theory, Duncan & Humphreys, 1989). This serial selection process is sensitive to distractor numerosity, and in these models it accounts for search efficiency or the degree to which RT exhibits an effect of display size. That our manipulation of cognitive load does not impact search efficiency suggests that under high load conditions it is not the case that a greater proportion of the distractors are selected by any serial search process. On the assumption that load does not affect the search process itself, we might envisage two other main stages that may be affected by load – stages of processing that operate prior to the commencement of the selection of items (pre-search), and stages of processing occurring after the search is terminated and the target selected, these processes may include target verification processes, and response selection.

Logan (1978) examined visual search for a letter target amongst letter distractors; over an extensive series of experiments he looked at which types of manipulation would interact with memory load. Consistent with the current work he showed that easing the task, by indicating the target location with a cue, did not interact with the effect of a memory load; participants were equally able to take advantage of the cue regardless of memory load. Additionally, he slowed down the encoding of the stimuli using a mask, and this did not interact with memory load, a finding consistent with stimulus encoding being load independent. Other manipulations, aimed to target aspects of response selection, also did not interact with memory load (present vs. absent responses, vocal vs. manual responses, or stimulus compatible vs. incompatible responses). From these studies, Logan (1978) suggested that memory load does not disrupt any of the stages of encoding, search, or response selection; rather, memory load disrupts a more general process of preparation whereby the general task priorities are set, and relevant representations are activated ready for the stimuli to be processed, a collection of processes often referred to as “task-set configuration” (e.g., Monsell, 1996). One explanation in the context of the current study is that a high memory load creates a delay in the speed at which any top-down biasing signals can be deployed. In the context of models such as Guided Search, memory load could potentially affect the time required to reset and re-enable a guiding template and for increased activation for moving elements to accrue in the activation map, prior to selection beginning, delaying overall response times. Importantly, recent research (e.g., Palmer et al., 2019; see also Wolfe et al., 2010) shows that implementing search guidance by colour is not immediately effective and can be a time consuming process. In particular, Palmer et al. (2019) showed how colour cues had to be available for some 300 ms prior to search items appearing in order to be fully effective. It may be the case that these processes are sensitive to memory load.

Several recent studies have also manipulated the state of knowledge of the participant regarding the target defining properties, in both simple feature (e.g., Wolfe et al., 2003) and conjunction (e.g., Friedman-Hill & Wolfe, 1995; Weidner & Müller, 2009) search. Perhaps of greatest relevance to the current study, Weidner and Müller (2009) asked participants to detect a large target amongst small distractors, these distractors also varied in their colours and motion. However, the target was always unique in either colour or motion amongst the large items. Across different conditions, participants either knew the target dimension but not the specific colour (e.g., red or green target) or they were uncertain about the dimension (e.g., red target or a target oscillating horizontally). Reaction times were slower when participants were uncertain of the dimension that would define the target, but this uncertainty did not increase the search slope, it only changed the overall search time. In order to explain their data, Weidner and Müller (2009) suggest that these overall decreases in RT can be understood in terms of the process of setting appropriate weights (e.g., upweighting the target defining dimension, see Muller et al., 2003) a process that takes some measurable amount of time. It is possible that holding a memory load similarly acts to delay this process of initial weight setting, prior to search commencing.

However, importantly, a recent study by Solman et al. (2011) looked again at the issue of whether the cost of a memory load (in this case a visual memory load) on search RT occurred before, during, or after the search process, in this case defined as the period during which participants make sequential eye-movements to candidate targets. The pre-search phase was defined as the period between stimulus on-set and the beginning of eye-movements to the search stimuli, the search phase was the period during which stimuli were inspected, and the post-search phase was the period between fixation on the target a response being made. Had the overall effect of memory load been one of preparation, or "task set configuration", it would have been legitimate to expect the effect to be found only or predominantly during the pre-search phase. However, this is not what happened, an overall slowing of *all* phases of the task was found. In order to explain their findings, in particular the finding of slowing of the search phase of the task despite no decrease in search efficiency, Solman et al. (2011) suggest that the ways in which participants sample the displays and accumulate evidence for target presence during the search differs as a function of memory load in a way that is independent of display size. With a higher memory load, participants make, overall, a greater number of eye-movements, regardless of display size, and their eye-movements land further away from the search items, suggesting that the quality of the information extracted during the search phase may be reduced (and reduced equally regardless of display size), leading to greater uncertainty and delaying response times.

Importantly, the study of Solman et al. (2011) shows that a manipulation may affect the search process without affecting search efficiency. The implication of this for the current study is that, rather than only the task set configuration being affected, we cannot rule out direct influences on the search process itself. One possibility here is that participants respond to the increased task difficulty of combining the two tasks by strategically increasing the amount of time they spend processing the displays in the high load condition. In the context of the Guided Search model, it may be that a stricter criterion for search termination is implemented in the context of a high memory load.

In summary, the current data are consistent with the idea that the ability to use motion to disregard a set of static distractors and select a set of moving elements is not affected by a cognitive load. Furthermore, at least in terms of the demand on domain-general cognitive control processes, it is no more demanding to ignore a set of static distractors that happen to have the target shape compared with those that have no features in common with the target. Further studies will be needed to determine if the overall cost that is observed stems from an overall increase in the time required to initially set up these guidance processes, or whether other processes related to accumulation of information in the search, or search termination, are responsible.

Open practices statement

Whilst the experiment was not preregistered. The data reported in this study are available for download at https://osf.io/3yjmp/.

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No potential conflict of interest was reported by the author(s).

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