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EARLY AND LATE SELECTION: EFFECTS OF LOAD, DILUTION AND SALIENCE

Topic Editors
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EARLY AND LATE SELECTION: EFFECTS OF LOAD, DILUTION AND SALIENCE

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Our visual system is constantly bombarded by a variety of stimuli, of which only a small part is relevant to the task at hand. As a result, goal-directed behavior requires a high degree of selectivity at some point in the processing stream. The precise point at which selection takes place has been the focus of much debate. Early selection advocates argue that the locus of selection is at early stages of processing and that therefore, unattended stimuli are not fully processed. In contrast, late selection theorists argue that attention operates only after stimuli have been fully processed. Evidence supporting both sides has been accumulated over the years and the debate played a central role in the attention literature for decades. Perceptual load theory was put forward as an intermediate solution: the locus of selective attention depends on task requirements. When load is high, selection is early. When load is low, selection is late. This solution has been widely accepted and the early/late debate has been, for the most part, set aside. However, recently, perceptual load theory has been challenged on both theoretical and methodological grounds. It has been argued that it is not load, but rather perceptual dilution salience and other perceptual factors that determine the efficacy of attentional selection, which would call for a reevaluation of the current status of both perceptual load theory and its proposed alternatives, and more broadly, the early/late selection debate. The goal of this Research Topic is to provide an up-to-date overview of both empirical evidence and theoretical views on these key questions.

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EDITORIAL
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Early and late selection: effects of load, dilution and salience

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Keywords: attention, early selection, late selection, perceptual load, dilution, salience

The present issue focuses on the classic question of early vs. late selection and evaluates the current status of the perceptual load theory that has been offered as an intermediate solution. Several of the papers compare or contrast perceptual load with an alternative explanation- perceptual dilution. The first group of papers report evidence that is inconsistent with the perceptual load theory but is generally consistent with the dilution theory.

Roper and Vecera (2013) report that flanker effects can be found under high perceptual load. Extending the duration of the display, and particularly of the relevant target, produces reliable congruency effects even under high perceptual load. The authors therefore argue that factors such as stimulus and encoding demands contribute to the load effect and that visual short term memory serves as an additional bottleneck when stimuli are briefly presented. Yeshurun and Marciano's (2013) findings also challenge the perceptual load theory. The authors found that task difficulty, as manipulated by degradation of visual information, did not affect attentional selection and flanker interference. This is in contrast to the claim that increasing sensory load increases distractor interference. Furthermore, the basic load effect was not replicated in all 4 experiments, and flanker effects were found even under high perceptual load.

Mevorach et al. (2014) tested patients with unilateral neglect and found that contralesional neutral elements eliminated the interference presented by a distractor. The authors argue that given the notion that no attentional resources are allocated to the contralesional field, perceptual load should not be affected by presenting items in the contralesional field. Instead they suggest that neutral stimuli dilute the flanker effect and that attentional selection is determined by dilution rather than load. This is in line with Benoni and Tsal (2013) who present a critical review of perceptual load theory. They challenge the theory's assumptions and supporting evidence, and provide supportive arguments for the alternative dilution theory.

Chen and Cave (2013) further studied the dilution effect. They present data that is consistent with dilution but not with perceptual load. However, they argue that the current conception of dilution is simplified. In particular the processing of neutral items is not only dependent on the number of stimuli present but also on complex interactions between top-down and bottom-up processes. Thus, both distractor and neutral elements in a multi element display compete for the same limited attentional resources.

In their opinion paper Linnell and Caparos (2013) argue that in accord with the perceptual load theory the spatial profile of attention was more focused when perceptual load was high and less focused when it was low. However in contrast to the theory this holds only when cognitive resources were available. Indeed, the authors emphasize the role of cognitive engagement in the task at hand and suggest that variations in perceptual load modulate task difficulty and this in turn alters cognitive engagement and motivation, factors often neglected in the study of attention.

More evidence for a strategic component in the seemingly automatic processing of task-irrelevant information comes from Biggs and Gibson (2013). They show that prior experience and situational expectations modulate the degree to which irrelevant information is processed. As they argue, this might render the assumption of a broad versus narrow allocation of visual attention in explaining effects of irrelevant information processing superfluous.

The review of Scalf et al. (2013) presents a hybrid neural competition theory that is generally consistent with both perceptual load and dilution theories. This theory reinforces the original view that low perceptual load is associated with a stronger impact of task-irrelevant information. As the authors point out, this might reflect different processing strategies in conditions with high and low perceptual load: While low perceptual load might allow for bottom-up-driven target selection, high perceptual load might call for top-down regulation. The latter leads to stronger filtering, which reduces the impact of task-irrelevant distractors.

The remaining papers use perceptual load theory as a direct or indirect context for studying other aspects of attentional selection. The role of working memory in regulating the degree to which distractors can be ignored is the focus of de Fockert's (2013) review. In support of the original assumption, the review provides strong evidence that higher working memory load makes it more difficult to ignore task-irrelevant distractors. This fits with the idea that working memory has an active role in gating irrelevant information.

Forster (2013) takes the perceptual load theory a step forward into the realm of mind-wandering and thought distraction. In her review she carefully distinguishes between different types of task relevancy and between external and internal (e.g., task-unrelated thoughts) sources of distraction. She argues that perceptual load theory is a powerful and largely universal framework to study distraction effects.

Parks et al. (2013) used SSVEPs together with ERPS to study the effect of attentional load in a go-no task. The findings reveal a center-surround configuration of both facilitation and suppression in the visual field.

Swallow and Jiang (2013) bring in a novel perspective by relating findings on the impact of perceptual load to the attentional boost effect—the observation that distractor processing can benefit from temporal synchronicity with target presentation. As they point out, the seemingly automatic processing of distractors with high perceptual load might reflect a kind of "intentional automatization": the cognitive system might be programmed to take in information automatically whenever being triggered by a target, suggesting that automatic processing might be a byproduct of intentional selection.

Folk (2013) makes an interesting conceptual distinction between processing costs produced by response-incompatible distractors on the one hand and search costs on the other. By combining aspects of the original perceptual-load paradigm and the classical singleton-search paradigm, he provides evidence that search costs remain even under conditions where the compatibility of distractors no longer affects processing.

Finally, Moher et al. (2013) tested selection processes without the explicit requirement of target identification. They found that detection performance remained high in spite of focal attention manipulations (i.e., target saliency, availability of cognitive resources, and familiarity) that eliminated identity-repetition effects. Thus, the authors conclude simple target detection is not dependent on focal attention.

We hope you will find this Research Topic interesting and informative. Enjoy your reading!

REFERENCES

Benoni, H., and Tsal, Y. (2013). Conceptual and methodological concerns in the theory of perceptual load. *Front. Psychol.* 4:522. doi: 10.3389/fpsyg.2013.00522

Biggs, A. T., and Gibson, B. S. (2013). Learning to ignore salient color distractors during serial search: evidence for experience-dependent attention allocation strategies. *Front. Psychol.* 4:326. doi: 10.3389/fpsyg.2013.00326

Chen, Z., and Cave, K. R. (2013). Perceptual load vs. dilution: the roles of attentional focus, stimulus category, and target predictability. *Front. Psychol.* 4:327. doi: 10.3389/fpsyg.2013.00327

de Fockert, J. W. (2013). Beyond perceptual load and dilution: a review of the role of working memory in selective attention. *Front. Psychol.* 4:287. doi: 10.3389/fpsyg.2013.00287

Folk, C. L. (2013). Dissociating compatibility effects and distractor costs in the additional singleton paradigm. *Front. Psychol.* 4:434. doi: 10.3389/fpsyg.2013.00434

Forster, S. (2013). Distraction and mind-wandering under load. *Front. Psychol.* 4:283. doi: 10.3389/fpsyg.2013.00283

Linnell, K. J., and Caparos, S. (2013). Perceptual load and early selection: an effect of attentional engagement? *Front. Psychol.* 4:498. doi: 10.3389/fpsyg.2013.00498

Mevorach, C., Tsal, Y., and Humphreys, G. W. (2014). Low level perceptual, not attentional, processes modulate distractor interference in high perceptual load displays: evidence from neglect/extinction. *Front. Psychol.* 4:966. doi: 10.3389/fpsyg.2013.00966

Moher, J., Ashinoff, B. K., and Egeth, H. E. (2013). Detection is unaffected by the deployment of focal attention. *Front. Psychol.* 4:284. doi: 10.3389/fpsyg.2013.00284

Parks, N. A., Beck, D. M., and Kramer, A. F. (2013). Enhancement and suppression in the visual field under perceptual load. *Front. Psychol.* 4:275. doi: 10.3389/fpsyg.2013.00275

Roper, Z. J. J., and Vecera, S. P. (2013). Response terminated displays unload selective attention. *Front. Psychol.* 4:967. doi: 10.3389/fpsyg.2013.00967

Scalf, P. E., Torralbo, A., Tapia, E., and Beck, D. M. (2013). Competition explains limited attention and perceptual resources: implications for perceptual load and dilution theories. *Front. Psychol.* 4:243. doi: 10.3389/fpsyg.2013.00243

Swallow, K. M., and Jiang, Y. V. (2013). Attentional load and attentional boost: a review of data and theory. *Front. Psychol.* 4:274. doi: 10.3389/fpsyg.2013.00274

Yeshurun, Y., and Marciano, H. (2013). Degraded stimulus visibility and the effects of perceptual load on distractor interference. *Front. Psychol.* 4:289. doi: 10.3389/fpsyg.2013.00289

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Response terminated displays unload selective attention

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Perceptual load theory successfully replaced the early vs. late selection debate by appealing to adaptive control over the efficiency of selective attention. Early selection is observed unless perceptual load (*p*-Load) is sufficiently low to grant attentional "spill-over" to task-irrelevant stimuli. Many studies exploring load theory have used limited display durations that perhaps impose artificial limits on encoding processes. We extended the exposure duration in a classic *p*-Load task to alleviate temporal encoding demands that may otherwise tax mnemonic consolidation processes. If the load effect arises from perceptual demands alone, then freeing-up available mnemonic resources by extending the exposure duration should have little effect. The results of Experiment 1 falsify this prediction. We observed a reliable flanker effect under high *p*-Load, response-terminated displays. Next, we orthogonally manipulated exposure duration and task-relevance. Counter-intuitively, we found that the likelihood of observing the flanker effect under high *p*-Load resides with the duration of the task-relevant array, not the flanker itself. We propose that stimulus and encoding demands interact to produce the load effect. Our account clarifies how task parameters differentially impinge upon cognitive processes to produce attentional "spill-over" by appealing to visual short-term memory as an additional processing bottleneck when stimuli are briefly presented.

Keywords: perceptual load, selective attention, visual short-term memory, visual awareness

The world around us is saturated with rich visual information; however, only a small subset of this information reaches conscious awareness at a given point in time. To accomplish this feat, the visual system operates with extreme prejudice by filtering all adequate visual stimuli to a small subset of privileged information. The outcome of this judicious behavior is a cognitive process known as selective attention. So that we may optimally behave on a variable environment, selective attention finely resolves visual input in accordance with biological imperatives. Attention selects stimuli that will aid an organism's pursuit of specific biological objectives, e.g., to locate food, to find sanctuary, to assess social relevance, to find a mate, et cetera (Most et al., 2007; Hodsoll et al., 2011). Optimal selection strategies give rise to adaptive behavior. However, this process is imperfect; sometimes attention selects more information than what is needed and sometimes less. Given a noisy input channel, on sheer probability alone it is rare that attention selects no more than desired and no less than necessary. Thus attentional control vacillates, throttling open to capture more of the environment when additional information is needed to complete a task and throttling down when narrower focus is needed to prevent distraction (Lien et al., 2010). In this fashion attention flexibly accommodates to the dynamic environment and is said to operate with a late locus when distractors command behavior, and an early locus at all other times (Yantis and Johnston, 1990; Miller 's 1991). That selective attention operates with an arbitrary amount of tolerance at all was not immediately understood. In fact, it took more than four decades to resolve the flexible locus hypothesis.

Early selection views prevailed in the 50s and 60s with pioneering attention studies (e.g., Cherry, 1953; Neisser, 1969; Treisman, 1969). However, the consensus shifted toward late selection views in the 70s and 80s (e.g., Deutsch and Deutsch, 1963; LaBerge, 1975; Allport, 1977; Duncan, 1980). Load theory was developed in the 90s to reconcile these disparate findings by appealing to the possibility of adaptive attentional control (Lavie and Tsal, 1994; Lavie, 1995). Load theory proposes that selective attention acts early, but is more efficient under high perceptual load (*p*-Load) than low *p*-Load (see Benoni and Tsal, 2013 for a concise review of load theory).

Load theory garners support from the flanker paradigm (e.g., Eriksen and Hoffman, 1973; Eriksen and Eriksen, 1974). In the simplest version of the flanker task, a target appears in the center of a homogeneous letter array (see **Figure 1**). The target takes on one of two possible identities, each of which is mapped onto a unique response key. Whereas congruent distractors share the target's response, incongruent distractors are mapped onto an alternate response key. The resulting trials are response congruent and incongruent, respectively. Incongruent distractors engender conflict during response selection and yield greater response time (RT) when observers must report the target's identity (Miller, 1991). This robust RT difference reflects the flanker effect and behaviorally indicates that the flanking distractors were processed to at least the point of meaning. Significant flanker interference effects epitomize late selection processes (Yantis and Johnston, 1990).

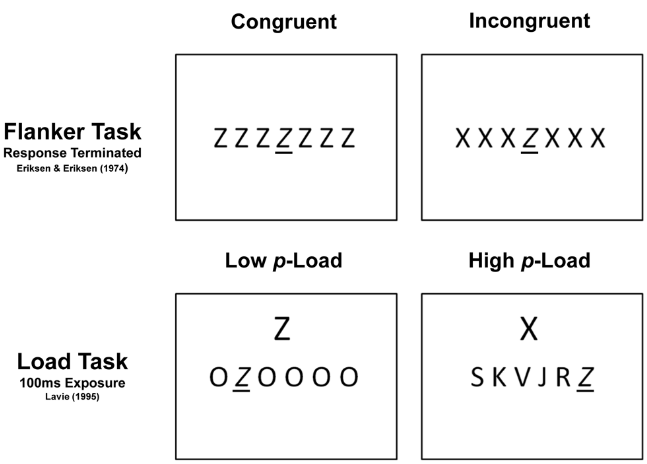

FIGURE 1 | Canonical Flanker and load tasks. The Eriksen Flanker task, top two panels, has both congruent and incongruent conditions. In the Eriksen Flanker task, the target is always located in the center. In the load task, lower two panels, the Flanker is either above or below the stimulus array and the relevant load is determined by the relationship between the distractors in the linear array and the target; additionally, the target can appear at any one of the six linear locations. The targets in these examples (all the letter "Z") have been italicized and underlined for distinction. Whereas the Flanker task employs response terminated displays, the load task uses brief exposure.

To address the possibility of a flexible locus of attention, Lavie (1995) revamped the flanker task by varying the difficulty to find the target. Heterogeneous distractors that resemble the target characterize high *p*-Load displays (Roper et al., 2013). Phenomenologically, these displays appear more cluttered than Eriksen and Eriksen's (1974) flanker displays (see **Figure 1**). Lavie proposed that an early filter is only established when attentional "resources" are fully taxed, that is, when *p*-Load is high. Under all other circumstances, load theory predicted surplus "resources" mandatorily "spill-over" to process task-irrelevant stimuli. Indeed, Lavie's results supported her predictions; significant flanker effects obtain only under low *p*-Load.

Despite the successes of *p*-Load theory, the nature of the attentional "resources" it invokes is unclear. Recent attempts to operationally define *p*-Load have successfully integrated load theory into the broader attention literature. Torralbo and Beck (2008) proposed that the load effect arises from the need to resolve low-level stimulus interactions between the target and distractors. Extending from Torralbo and Beck (2008); Lavie and Cox (1997), and Duncan and Humphreys, 1989), we demonstrated a clear role for target-distractor similarity and distractor homogeneity in the context of *p*-Load (Roper et al., 2013). Using identical stimuli in a visual search task and a canonical *p*-Load task, we discovered a close correspondence between search efficiency and flanker effect magnitude. We found that low *p*-Load displays were searched efficiently, whereas high *p*-Load displays were not. These findings suggest that load might be defined by appealing to bottom-up stimulus interactions that are known to affect visual search. However, close consideration of the typical *p*-Load task suggests that bottom-up stimulus factors do not completely account for the "resources" of *p*-Load theory.

At least two component processes are at play when an observer performs the canonical *p*-Load task: (1) feature-based attention needed to resolve inter-stimulus competition (Lavie and Cox, 1997; Torralbo and Beck, 2008; Roper et al., 2013), and (2) encoding-based processes needed to endogenously represent fleeting stimuli (Jolicœsur and Dell'Acqua, 1999). The thrust of our current work was to closely examine specifically how exposure duration operates to bring about encoding challenges. This was done so that we may better characterize the nature of attentional "resources" – feature-based and encoding-based – that are responsible for "spill-over."

To date, nearly all load studies have employed brief target display durations. For example, Lavie's (1995) original work incorporated 100 ms stimulus exposure durations. Similarly, a concise but representative literature review revealed that subsequent load studies have followed suit with exposure durations ranging from 17 to 200 ms, having a modal duration of 100 ms (Lavie and Cox, 1997; Bavelier et al., 2000; Handy and Mangun, 2000; Lavie and Fox, 2000; Lavie and de Fockert, 2003, 2005; MacDonald and Lavie, 2008; Torralbo and Beck, 2008; Benoni and Tsal, 2010; Caparos and Linnell, 2010; Elliott and Giesbrecht, 2010; Gaspelin et al., 2012; Roper et al., 2013). Brief exposure durations were originally adopted to preclude eye movements putatively as a means to disentangle overt from covert attentional processes (Lavie and Cox, 1997). The practice of brief exposure duration in load tasks deviates from the original flanker interference studies from which load theory is drawn as those pioneering studies employed display durations of 1000 ms (Eriksen and Hoffman, 1973; Eriksen and Eriksen, 1974). The use of limited display durations is not problematic *per se*, but failing to adequately recognize the role of exposure duration can be misleading when interpreting load theory.

On the assumption that brief exposure durations impose encoding demands, we manipulated the exposure duration of the stimulus array in a typical *p*-Load paradigm. We hypothesized that if the flanker effect solely depends upon display complexity (i.e., *p*-Load), then indefinitely extending the exposure duration, thereby reducing encoding demands, should have no bearing on the behavioral outcome (i.e., no flanker effect would be present under high *p*-Load). We orthogonally manipulated *p*-Load (canonical low *p*-Load vs. high *p*-Load) and exposure duration (100 ms vs. response-terminated). If temporal demands play no role in "spill-over," then we expect to observe a robust load effect – flanker effect under low but not high *p*-Load. However, if temporal demands prevent robust flanker processing under high *p*-Load, then extending the exposure duration will increase the opportunity to sample the flanker thereby promoting a flanker effect.

To preview our results, we find a significant flanker effect under high *p*-Load when displays are response terminated. Experiment 1 suggests that brief exposure duration imposes encoding restrictions that manifest as the load effect. In Experiment 2, we orthogonally manipulated exposure duration and task-relevance by briefly presenting the target array (Experiment 2a) and the flanker (Experiment 2b). We found that, under high *p*-Load, interference effects are abolished when the target array is briefly displayed, but not when the temporal restriction falls on the flanker alone. As hypothesized by load theory, task-relevance must be considered to accurately describe how feature competition and temporal demands interact to engage selective attention.

EXPERIMENT 1

METHOD

Observers

Twenty-four University of Iowa undergraduates participated for course credit. All had normal or corrected-to-normal vision.

Apparatus

An Apple Mac Mini computer displayed stimuli on a 17-inch CRT monitor and recorded keyboard responses and latencies. The experiment was controlled using MATLAB and the Psychophysics toolbox (Brainard, 1997). Observers were seated 60 cm from the monitor.

Stimuli and procedure

The stimuli and procedure were modeled after Lavie's (1995) load experiments. A target letter, equally likely to be X or Z, was randomly positioned in a six-item linear array (see **Figure 1**). The target was accompanied by five non-target letters which occupied the remaining positions along the horizontal. The letters K, V, S, J, and R comprised the high *p*-Load non-target set and the letter O, repeated five times, comprised the low *p*-Load, non-target set. The target and non-target letters were presented in uppercase, Helvetica font. They subtended a visual angle of 1.79° vertically and 1.55° horizontally and were separated by 0.60° (edge-to-edge). On every trial, a task-irrelevant flanker appeared 5.80° above or below the linear target array. The flanker was cortically magnified and subtended a visual angle of 2.84° vertically and 2.48° horizontally. Observers were encouraged to ignore the flanker. All stimuli were presented in black on a white background.

Observers were instructed to respond to the target via keyboard button press as quickly and accurately as possible. Observers pressed the "Z" key with the index finger one hand and the "?" key with the other index finger to indicate whether the target was Z or X. The flanker was equally likely to be response congruent (Z when the target was Z, likewise for the X), incongruent (X when the target was Z, or vice versa), or neutral (P which was not associated with any response).

Each trial began with a central black fixation dot that appeared for 1000 ms. The target array and the flanker immediately replaced the fixation dot (see **Figure 2**). These stimuli were briefly displayed (100 ms) or remained until observer response. This exposure duration manipulation (brief or response-terminated) was blocked along with *p*-Load (high or low) thereby creating four unique block types. Block order was counterbalanced to produce 24 unique versions of the experiment (4! = 24). Each observer completed four blocks of 98 trials. Prior to the experiment, observers completed a 32-trial practice block. The results of the practice blocks were excluded from analyses.

RESULTS AND DISCUSSION

Mean correct RTs were computed for each observer as a function of load, exposure duration, and the nature of the critical distractor (congruent, neutral, and incongruent). Response latencies ± 2.5 SD from the individual means were excluded from the analysis (see **Figure 3**); this trimming excluded 2.8% of the data.

A three-factor repeated measures ANOVA (2 × 2 × 2) was conducted on the RT data, with display *p*-Load (high vs. low), *m*-Load (100 ms vs. response-terminated), and flanker congruency (neutral vs. incongruent) as factors. We observed a main effect of *p*-Load, $F(1, 23) = 119.44$, $p < 0.0005$, $\eta_p^2 = 0.84$. RT was faster for low *p*-Load (*Mean* = *M* = 554 ms) than high *p*-Load (*M* = 840 ms). We also observed a main effect of *m*-Load, $F(1, 23) = 11.76$, $p = 0.002$, $\eta_p^2 = 0.34$. RT was faster when the display was briefly exposed (*M* = 652 ms) than when it was response-terminated (*M* = 742 ms). Additionally, we observed a significant main effect of flanker congruency, $F(1, 23) = 34.4$, $p < 0.0005$, $\eta_p^2 = 0.60$. RT was faster in the neutral condition (*M* = 684 ms) than in the incongruent condition (*M* = 710 ms). Most important, we observed a significant three-way interaction, $F(1, 23) = 4.39$, $p = 0.047$, $\eta_p^2 = 0.16$, and a significant two-way interaction between *m*-Load and congruency, $F(1, 23) = 6.26$, $p = 0.020$, $\eta_p^2 = 0.21$ which align our results with Lavie's original finding (1995).

Accuracy performance paralleled RT effects (see **Table 1**). A three-factor repeated measures ANOVA (2 × 2 × 2) was conducted on accuracy data, with display *p*-Load (high vs. low), *m*-Load (100 ms vs. response-terminated), and flanker congruency (neutral vs. incongruent) as factors. We observed a main effect of *p*-Load, $F(1, 23) = 29.39$, $p < 0.0005$, $\eta_p^2 = 0.56$. Accuracy was better for low *p*-Load (*M* = 0.95, SE = 0.005) than high *p*-Load (*M* = 0.91, SE = 0.008). We also observed a main effect of *m*-Load, $F(1, 23) = 68.77$, $p < 0.0005$, $\eta_p^2 = 0.75$. Accuracy was better when the display was response terminated (*M* = 0.96, SE = 0.006) than when it was brief (*M* = 0.90, SE = 0.007). Additionally, we observed a significant main effect of flanker congruency, $F(1, 23) = 33.83$, $p < 0.0005$, $\eta_p^2 = 0.60$. Accuracy was better in the neutral condition (*M* = 0.94, SE = 0.005) than in the incongruent condition (*M* = 0.92, SE = 0.006). We observed a significant two-way interaction, $F(1, 23) = 29.66$, $p < 0.0005$, $\eta_p^2 = 0.56$. No other comparisons reached significance.

The results of the brief display condition replicated the load effect in that we observed a significant flanker effect for low but not high *p*-Load. The response-terminated displays produced a different pattern of results. Here we observed flanker effects irrespective of *p*-Load, indicating that display complexity interacts with temporal demands to produce the load effect.

This finding shares affinity with Miller's (1991) assertion that even with fairly high *p*-Load, unattended flankers are processed semantically to some degree. To support his claim, Miller, 1991, Experiment 9) measured observers' RT to identify a target letter in a heterogeneous display. Miller sought to delay the recognition of the flankers with respect to the target by presenting the target array slightly before the flankers. The flankers were presented in the periphery after a variable stimulus onset asynchrony (SOA) of 250, 350, and 450 ms. Significant flanker effects obtained regardless of SOA. Importantly, Miller used response terminated displays. The current findings reconcile the discrepancy between Miller's

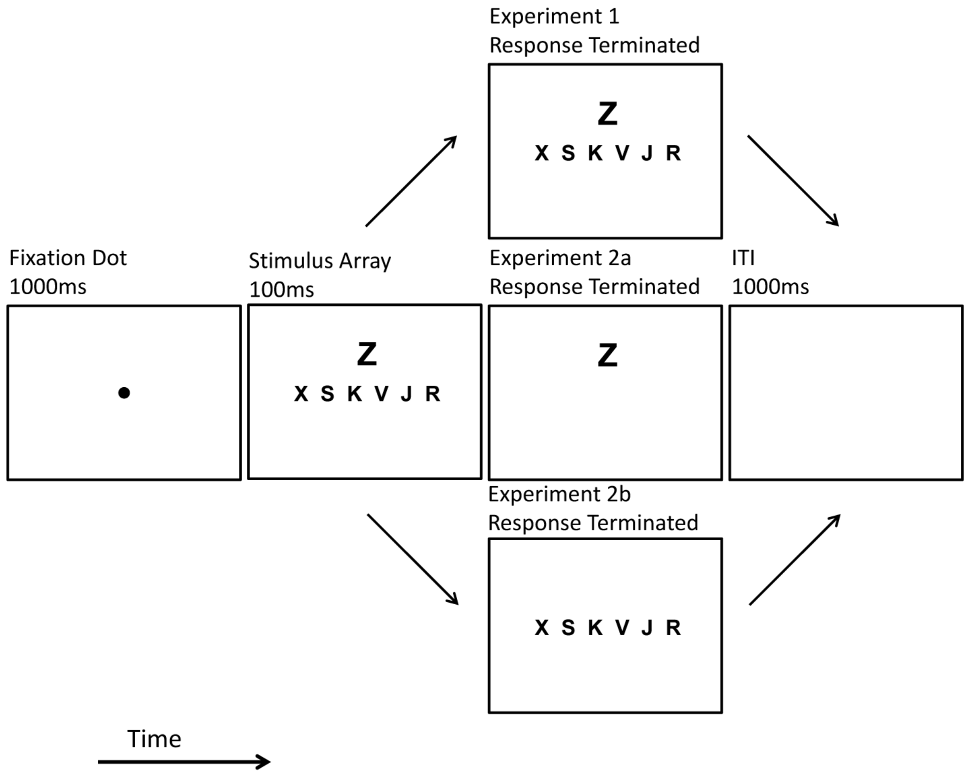

FIGURE 2 | Trial schematic. Example of high *p*-Load, response terminated displays as presented in Experiments 1 and 2.

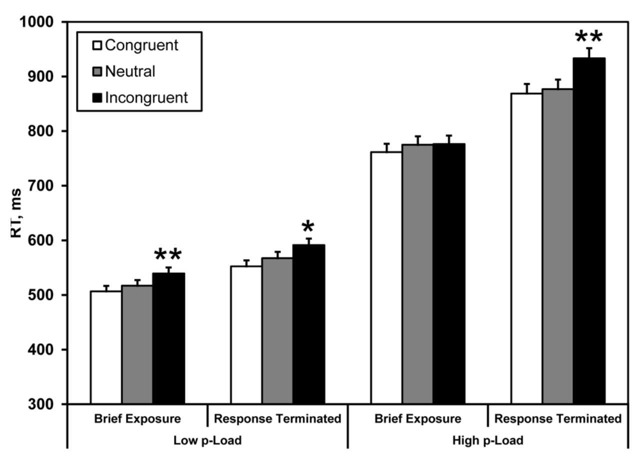

FIGURE 3 | Mean correct RT in Experiment 1. Briefly exposed stimuli were presented for 100 ms – all other stimuli were response-terminated. Asterisks denote significance from neutral condition: $*p < 0.05$, $**p < 0.01$. Error bars represent 95% within-observers confidence intervals (Loftus and Masson, 1994; Morey, 2008).

load manipulation and those typically used to study *p*-Load on attention (e.g., Lavie, 1995).

Whereas Experiment 1 explored the demands marshaled by whole-display temporal constraints, Experiments 2a and 2b were designed to address whether *task-relevance* interacts with the temporal demands of the display to produce "spill-over." Stimulus *relevance* has been critical to load theory's interpretation since its inception (Lavie and Tsal, 1994). Only when the relevant task *p*-Load is low, will surplus attentional "resources" mandatorily "spill-over." Our account makes the strong prediction that the task-relevant array's exposure duration is most critical to witness load effects. When presented briefly, attention samples the task-relevant region at the expense of the flanker provided that the feature-based demands are sufficiently great. This leads to the natural prediction that briefly presenting the target array while leaving the flanker present until response will abolish flanker effects. This sort of prediction is at great odds with intuition. It seems irrational to expect the flanker to show no influence on behavior when it is

Table 1 | Experiment 1: accuracy performance.

		Flanker type					
		Incongruent		Neutral		Congruent	
		M	SD	*M*	SD	*M*	*SD*
Low load	Brief display	0.93	0.05	0.96	0.04	0.96	0.04
	Resp. term.	0.95	0.04	0.97	0.02	0.97	0.02
High load	Brief display	0.85	0.07	0.87	0.06	0.89	0.06
	Resp. term.	0.95	0.04	0.96	0.03	0.97	0.03

present on-screen for the entire duration of the trial and is the only on-screen stimulus 100 ms into the trial. We designed Experiment 2a to test this hypothesis and find that when encoding demands are placed on the task-relevant array but not the flanker, "spill-over" is prevented despite the near-certain probability that the flanker was visibly isolated.

EXPERIMENT 2

In Experiment 2a the target array offset after 100 ms, but the flanker persisted until response. We employed the converse relationship in Experiment 2b – the flanker offset after 100 ms, but the target array persisted until response.

METHOD

The method of Experiment 2a was identical to Experiment 1 except that the offset of the target array and the flanker were asynchronous. Thus, in lieu of categorical response terminated displays such as those in Experiment 1, we introduce hybrid displays in Experiment 2 where 100 ms after stimulus onset, either the task-relevant or task-irrelevant portion of the display was removed – the lave being response terminated. Whereas Experiment 2a was characterized by the asynchronous removal of the target array, Experiment 2b was characterized by the asynchronous removal of the flanker. All stimuli were removed without backward masks. Observers were 48 (24 per experiment) University of Iowa undergraduates. All observers reported normal or corrected-to-normal vision. Experiments 2a and 2b were analyzed separately.

RESULTS AND DISCUSSION

Experiment 2a

Mean correct RTs were computed for each observer as a function of p-Load, brief exposure (whole display or hybrid), and the nature of the critical distractor (congruent, neutral, and incongruent). Response latencies $\pm$ 2.5 SD from the individual means were excluded from the analysis (see **Figure 4**); this trimming eliminated 2.9% of the data.

Response time data were analyzed identically to Experiment 1 by carrying out a 2 × 2 × 2 repeated-measures ANOVA. We observed a main effect of load, $F(1, 23) = 235.60$, $p < 0.0005$, $\eta_p^2 = 0.91$. RT was faster under low p-Load ($M = 528$ ms) than high p-Load ($M = 778$ ms). Additionally, we observed a significant main effect of flanker congruency, $F(1, 23) = 6.18$, $p = 0.021$, $\eta_p^2 = 0.21$. Neutral RT ($M = 646$ ms) was faster than incongruent RT ($M = 661$ ms). The two-way interaction between p-Load and congruency was marginally significant, $F(1, 23) = 4.20$, $p = 0.052$, $\eta_p^2 = 0.15$.

Accuracy performance paralleled RT effects (see **Table 2**). A three-factor repeated measures ANOVA (2 × 2 × 2) was conducted on accuracy data, with display p-Load (high vs. low), m-Load (100 ms vs. response-terminated), and flanker congruency (neutral vs. incongruent) as factors. We observed a main effect of p-Load, $F(1, 23) = 28.08$, $p < 0.0005$, $\eta_p^2 = 0.55$. Accuracy was better for low p-Load ($M = 0.95$, SE $= 0.007$) than high p-Load ($M = 0.90$, SE $= 0.010$). We also observed a main effect of brief flanker, $F(1, 23) = 28.88$, $p < 0.0005$, $\eta_p^2 = 0.56$. Accuracy was better when just the flanker was brief ($M = 0.95$, SE $= 0.006$) than when the entire display was brief ($M = 0.89$, SE $= 0.012$). Additionally, we observed a significant main effect of flanker congruency, $F(1, 23) = 15.00$, $p = 0.001$, $\eta_p^2 = 0.40$. Accuracy was better in the neutral condition ($M = 0.93$, SE $= 0.007$) than in the incongruent condition ($M = 0.91$, SE $= 0.008$). We observed a significant two-way interaction, $F(1, 23) = 27.73$, $p < 0.0005$, $\eta_p^2 = 0.5$. No other comparisons reached significance.

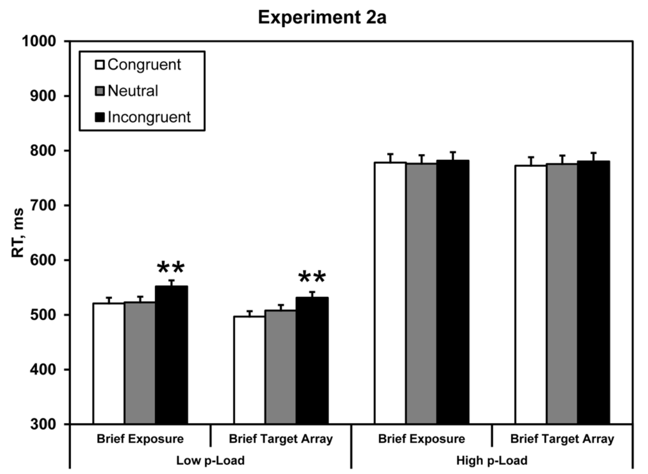

FIGURE 4 | Mean correct RT in Experiment 2a. Briefly exposed stimuli were presented for 100 ms – all other stimuli were response-terminated. Asterisks denote significance from neutral condition: $^{**}p < 0.01$. Error bars represent 95% within-observers confidence intervals (Loftus and Masson, 1994; Morey, 2008).

Experiment 2a demonstrated that when the task-relevant array is temporally constrained, the flanker fails to exert a behavioral effect despite being the only on-screen stimulus for the majority of the trial. Thus, the load effect is closely linked with the exposure duration of the target array, not the flanker. Although the flanker lingered until response, it failed to exert an interference effect. We reason that briefly presenting the target imposes a mnemonic load (m-Load) on processing. This m-Load consumes mnemonic resources to endogenously represent the flanker thereby precluding robust flanker processing.

We take it as fact that the absence of a significant interference effect means that the flanker's identity did not reach response selection. However, we cannot know for certain where the system ceased processing the flanker during its initial sweep. If we assume that the flanker needs to be consolidated into visual short-term memory (VSTM) before it can exert a downstream effect, then the absence of a downstream effect suggests two possibilities: (1) limited attentional "resources" initially deploy to preserve the representation of the fleeting task-relevant region at the cost of the task-irrelevant region, and (2) the flanker's representation simply decays too fast. Experiment 2a falsifies the second possibility. If the flanker doesn't reach response selection because it simply decays, then when we prevent decay by leaving it on-screen until response we ought to expect a flanker effect irrespective of any feature or encoding demand placed on the task-relevant array. However, we

Table 2 | Experiment 2: accuracy performance.

			Flanker type					
			Incongruent		Neutral		Congruent	
			M	SD	*M*	SD	*M*	SD
Exp. 2a	Low load	Brief display	0.93	0.05	0.95	0.03	0.97	0.03
		Brief Flanker	0.94	0.06	0.96	0.03	0.96	0.02
	High load	Brief display	0.83	0.09	0.85	0.11	0.85	0.12
		Brief Flanker	0.95	0.04	0.96	0.03	0.95	0.05
Exp. 2b	Low load	Brief display	0.94	0.05	0.96	0.04	0.95	0.05
		Brief target	0.93	0.05	0.96	0.04	0.97	0.02
	High load	Brief display	0.84	0.08	0.88	0.06	0.87	0.06
		Brief target	0.93	0.09	0.95	0.09	0.94	0.08

observed the contrary. Thus, in order for robust flanker processing all other encoding restrictions must be mitigated. Therefore, the flanker effect does not reside with the duration of the flanker. Furthermore, when we shorten its longevity but leave the task-relevant array until response, we should expect to obtain the canonical load effect. Experiment 2b was designed to test this hypothesis.

Experiment 2b

Mean correct RTs were computed for each observer as a function of *p*-Load, brief exposure (whole display or hybrid), and the nature of the critical distractor (congruent, neutral, and incongruent). Response latencies ± 2.5 SD from the individual means were excluded from the analysis (see **Figure 5**); this trimming eliminated 2.9% of the data.

Response time data were analyzed identically to the previous experiments by carrying out a 2 × 2 × 2 repeated-measures ANOVA. We observed a main effect of load, $F(1, 23) = 164.98$, $p < 0.0005$, $\eta_p^2 = 0.88$. RT was faster for low *p*-Load ($M = 542$ ms) than high *p*-Load ($M = 847$ ms). We also observed a main effect of target array duration, $F(1, 23) = 11.58$, $p = 0.002$, $\eta_p^2 = 0.34$. RT was faster when the entire display was briefly presented ($M = 642$ ms) as opposed to the flanker alone ($M = 747$ ms). Additionally, we observed a significant main effect of flanker congruency, $F(1, 23) = 11.66$, $p = 0.002$, $\eta_p^2 = 0.34$. Neutral RT ($M = 684$ ms) was faster than incongruent RT ($M = 705$ ms). Most important, we observed a significant two-way interaction between *p*-Load and flanker congruency, $F(1, 23) = 6.02$, $p = 0.022$, $\eta_p^2 = 0.21$. These results replicate our findings from Experiment 1 and Lavie's original perceptual load demonstration.

Accuracy performance paralleled RT effects (see **Table 2**). A three-factor repeated measures ANOVA (2 × 2 × 2) was conducted on accuracy data, with display *p*-Load (high vs. low), *m*-Load (100 ms vs. response-terminated), and flanker congruency (neutral vs. incongruent) as factors. We observed a main effect of *p*-Load, $F(1, 23) = 11.70$, $p = 0.002$, $\eta_p^2 = 0.34$. Accuracy was better for low *p*-Load ($M = 0.95$, SE = 0.006) than high *p*-Load ($M = 0.89$, SE = 0.017). We also observed a main effect of brief flanker, $F(1, 23) = 9.96$, $p = 0.004$, $\eta_p^2 = 0.30$. Accuracy was better when just the flanker was brief ($M = 0.94$, SE = 0.012) than when the entire display was brief ($M = 0.89$, SE = 0.013). Additionally, we observed a significant main effect of flanker congruency, $F(1, 23) = 56.53$, $p < 0.0005$, $\eta_p^2 = 0.71$. Accuracy was better in the neutral condition ($M = 0.93$, SE = 0.010) than in the incongruent condition ($M = 0.91$, SE = 0.010). We observed a significant two-way interaction, $F(1, 23) = 10.05$, $p = 0.004$, $\eta_p^2 = 0.30$. No other comparisons reached significance.

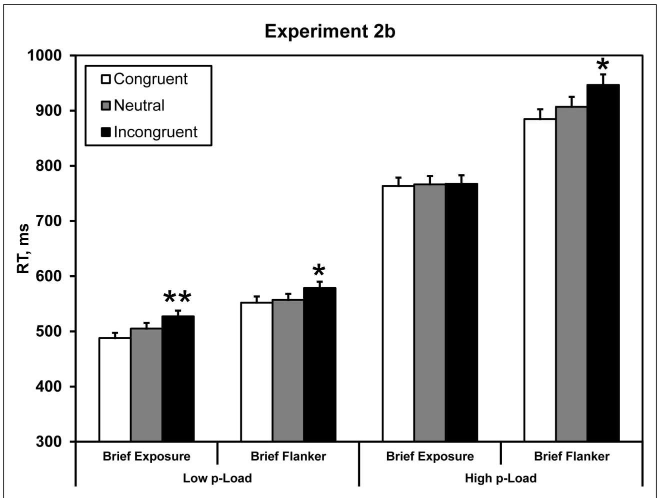

FIGURE 5 | Mean correct RT in Experiment 2b. Briefly exposed stimuli were presented for 100 ms – all other stimuli were response-terminated. Asterisks denote significance from neutral condition: $*p < 0.05$, $**p < 0.01$. Error bars represent 95% within-observers confidence intervals (Loftus and Masson, 1994; Morey, 2008).

In Experiment 2b we obtained a significant flanker effect under high *p*-Load when the flanker was briefly presented but the target array lingered until response. Although the flanker was briefly presented it nevertheless exerted a downstream effect. We propose that when briefly presented, the flanker's icon can be sampled provided that the search stimuli remain visible. This proposition conforms to Experiment 1 and 2a in that both high stimulus competition and great encoding demands interact to produce the load effect. By briefly presenting the flanker in Experiment 2b, we incrementally loaded mnemonic processing.[1] Because the majority of stimuli remained onscreen, however, spare resources were available to process the fleeting flanker.

Experiments 1 and 2 indicate that the load effect vanishes when observers are not given strict encoding demands. These results point to the visual system's highly adaptive nature; when items are in jeopardy of decaying away, the system can optimize attentional allocation toward task-relevant stimuli at the expense of task-irrelevant stimuli. Lavie demonstrated that high *p*-Load induces this response. We have demonstrated that great encoding demands also engage selection. Thus, mnemonic "resource" limitations can serve as an additional processing bottleneck that activates selection and drives the load effect.

GENERAL DISCUSSION

Historically, the load effect has been thought to be driven entirely by perceptual-level resource demands, not data limitations (Lavie and de Fockert, 2003); however, our experiments have shown that in fact both *p*-Load and *m*-Load play similar, but distinct roles in distractor processing. In Experiment 1, we extended the exposure duration of a canonical load task and demonstrated that when the encoding restrictions imposed by brief displays are lifted, flanker effects obtain despite high *p*-Load. In Experiment 2b, we demonstrated the importance of task-relevance when considering the influence that *m*-Load has on selective attention. We observed a significant interference effect when the flanker was briefly exposed but the task-relevant array remained until response. This finding starkly contrasts with Experiment 2a, the inverse situation, where the flanker remained until response but the task-relevant array was briefly exposed. In Experiment 2a, although the flanker remained on-screen, it failed to exert a behavioral effect under high *p*-Load. The results provide a possible compromise for load theory that incorporates *m*-Load and *p*-Load as potential restrictions that interact to set the locus of selective attention. We cannot observe *p*-Load effects without implementing an *m*-Load; conversely, we cannot observe *m*-Load effects without implementing a *p*-Load.

Figure 6 highlights the individual contributions of *m*-Load and *p*-Load on distractor processing. Tasks with high *m*-Load (points A and B in **Figure 6**) but with low *p*-Load (point A) lead to significant flanker effects as has been shown previously (Lavie and Tsal, 1994). Experiment 1 demonstrated that tasks with high *p*-Load (points D and B in **Figure 6**) but without accompanying high *m*-Load (point D) also gives rise to significant flanker effects. Therefore adequate consideration must be given to *p*-Load and *m*-Load to fully capture

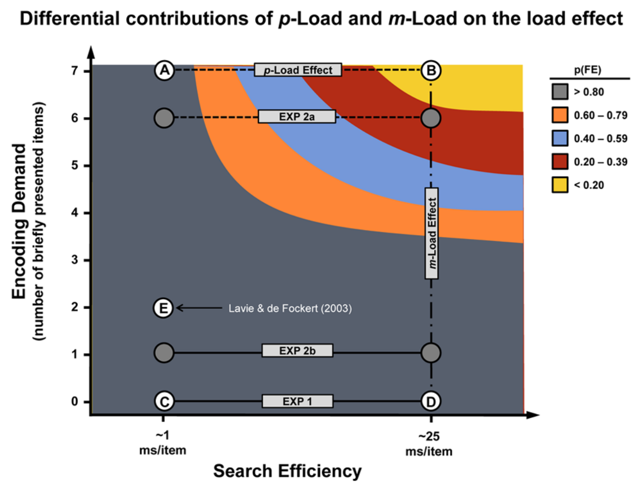

FIGURE 6 | Load effect "resources." This empirically derived model illustrates two forms of "resource" demand – feature- and encoding-based – that impinge upon selective attention to produce the load effect (denoted by dashed lines). The vertical axis denotes the *m*-Load and is quantified as the number of briefly exposed display stimuli. The horizontal axis denotes the *p*-Load and is quantified in terms of the search efficiency of the displays. These values are estimated based on our previous work exploring the role of visual search and load (Duncan and Humphreys, 1989; Roper et al., 2013). Points A and B represent the canonical low *p*-Load and high *p*-Load tasks, respectively. Tasks represented by point A and B served as control conditions for Experiments 1 and 2. Low *p*-Load was characterized by a conspicuous target (search efficiency ~1 ms/item), whereas high *p*-Load was characterized by an inconspicuous target (search efficiency ~25 ms/item) – both conditions are characterized by high *m*-Load (7 stimuli at 100 ms exposure). Experiments 2a and 2b, denoted by filled circles, were hybridized and fall between line segments AB and CD in terms of *m*-Load (see Experiment 2 methods). Point C represents a low *m*-Load, low *p*-Load task and point D represents a low *m*-Load, high *p*-Load task (both unique to Experiment 1). Point E reflects a high *m*-Load, low *p*-Load task (Experiment 2, Lavie and de Fockert, 2003). N.B., although feature competition and encoding demands can be manipulated orthogonally, it is not entirely clear whether these factors are psychologically independent. The shape of the curve is intended for demonstration only.

the load effect. In Experiments 2a and 2b, we demonstrated that the *m*-Load needs to be placed on the task-relevant array, not the flanker, to obtain the load effect. We speculate that this is because there is more visual information that needs to be encoded when the six-item target array is briefly presented. These encoding demands are compounded when *p*-Load is great. As demonstrated in Experiment 2a, when mnemonic resources are preoccupied by the necessity to quickly encode the target array, the flanker fails to engender an interference effect even when it remains on-screen until response.

SENSORY AND ENCODING DEMANDS

Lavie and de Fockert (2003) increased task difficulty by degrading the target stimulus and decreasing exposure duration (50 ms) in a low *p*-Load task. They argued that the flanker effect would be abolished only if the imposed data limitations play a role in selective attention. The data revealed a significant flanker effect, suggesting that data limitations do not drive *p*-Load. Such a conclusion runs counter to our current findings, but can be explained by carefully inspecting **Figure 6**. First, we assert that due to relatively low

[1] We would like to stress that the flanker was not backward-masked in Experiment 2. Therefore, based on the presence of the flanker effect in high *p*-Load, it is likely that the identity of the flanker was obtained from the visual icon (Averbach and Coriell, 1961; Phillips, 1974). We reason that the visual system consolidated the flanker into VSTM to prevent complete decay. Indeed visual transients, such as abrupt-offsets, have been shown to capture attention (Pratt and McAuliffe, 2001), and attention-capturing stimuli are automatically consolidated in VSTM (Schmidt et al., 2002; Belopolsky et al., 2008). However, we acknowledge the possibility that the flanker circumvented VSTM, but this scenario is less likely. Our own investigations have revealed that when the flanker is backward-masked, canonical load effects obtain (Roper et al., 2011).

p-Load and 100 ms exposure duration, conventional low *p*-Load tasks fall near point A in **Figure 6**. From Norman and Bobrow (1975) we know that masked, degraded, and brief displays constitute data limitations. If these arguments hold, then it follows that the flanker task with a degraded target and very limited exposure duration as described above and tested by Lavie and de Fockert (2003) would deviate from point A in the vertical direction only. Our account predicts a significant flanker effect under these conditions. Therefore, we propose that the load effect arises from attentional resource demands imposed by the display's perceptual characteristics coupled with the encoding demands introduced by brief stimulus presentation. Limiting the exposure duration prevents complete processing of all available stimuli due the severe capacity limitations inherent to memory consolidation and representation. When this happens, the least relevant stimuli are excluded from robust processing.

SELECTIVE ATTENTION AND VISUAL SHORT-TERM MEMORY

In three experiments we have demonstrated that the load effect dissipates when the temporal demands to quickly encode the task-relevant stimuli are removed. Counter-intuitively, the likelihood of processing the task-irrelevant flanker does not reside in the longevity of the flanker itself but rather with the availability of attentional "resources." These findings implicate VSTM capacity limitations as a substantial bottleneck for attentional processing.

Briefly presented stimuli place temporal demands on visual processing (Jolicœsur and Dell'Acqua, 1999). Thus, fleeting environmental information must be internally represented before it reaches downstream processing. We propose that limited display durations increase temporal encoding demands. Exactly where along the stream of processing these demands exert the greatest effect is not precisely known; however, Roper and Vecera (2013) demonstrated that increments in VSTM load produced greater selective attention in a concurrently performed *p*-Load task. Konstantinou and Lavie (2013) replicated this effect in a standard selection task. Thus the reliance on VSTM to identify the target and program the correct response has been empirically founded. Furthermore, these two recent studies demonstrate that domain-specific *m*-Loads impede distractor processing but domain-general *m*-Loads exacerbate the distraction effect. Because VSTM capacity is spatially and temporally restricted (Zhang and Luck, 2008), when stimuli are too numerous or too complex, selective attention can prioritize entrance into VSTM based on task relevance. In the typical load task, the task-relevant search array appears around fixation, and the flanker appears at a location never occupied by a target. Observers can optimally search for the target by segregating the display based on task-relevance, allowing attention to prioritize likely target locations over unlikely target locations. We hypothesize that under high *p*-Load, observers prioritize potential target locations for entry into VSTM at the expense of the task-irrelevant flanker. Under low *p*-Load, ample VSTM capacity exists, and attention need not precisely prioritize entry into VSTM – in fact, based on the evidence, under low *p*-Load, all stimuli are mandatorily processed (Lavie, 1995). This account need only assume that the flanker be encoded in VSTM prior to exerting behavioral effects – a safe assumption given that access to VSTM satisfies a necessary, but not sufficient, condition to witness competition at the output stage.

This work converges with recent work by Konstantinou et al. (2012), who found that a concurrent VSTM load attenuated contrast sensitivity. Decreased brain metabolism in primary and tertiary visual areas (V1-V3) accompanied the contrast sensitivity decrement. Extending from Bundesen (1990) and Bundesen et al.'s (2005) Theory of Visual Attention (TVA), Kyllingsbæk et al. (2011) demonstrated that load effects are best explained by appealing to a model that incorporates processing capacity and VSTM capacity limits. Participants reported the identity of several targets in briefly presented displays while ignoring flanking letters. Target identification declined as the number of flankers increased, a result not readily predicted by load theory. Kyllingsbæk et al. (2011) argued TVA could readily explain their results – as the number of flankers increases, flankers are more likely to enter VSTM, which reduces the likelihood that a target will enter VSTM.

The previously described extant studies bolster the current work and provide direct tests to support our conclusion that the load effect relies upon the availability of VSTM resources. Thus it is reasonable to conclude that load, as it has been previously tested, is not exclusively perceptual but rather partly determined by mnemonic processing limitations. This assertion is based upon work that demonstrates that the bandwidth of mnemonic processing is limited, but the bandwidth of perceptual processing is virtually limitless (Sperling, 1960; Averbach and Coriell, 1961; Potter, 1976; Coltheart, 1980; Di Lollo, 1980; Jolicœsur and Dell'Acqua, 1998; Vogel et al., 1998). These findings indicate that selective attention may play as vital a role in VSTM as perception (Schmidt et al., 2002).

LOAD THEORY AND DILUTION

Tsal and Benoni (2010) have recently proposed that the load effect arises from diluting the display with additional neutral stimuli and not *p*-Load itself. To support their proposition, they carefully crafted a high-dilution display that was nevertheless low in *p*-Load. This was accomplished by placing neutral stimuli – that putatively dilute the flanker – at otherwise task-irrelevant locations. They hypothesized that if dilution, not *p*-Load, determines the locus of selection, then these high-dilution, low *p*-Load displays will fail to produce a flanker effect. Their predictions were confirmed; neutral but otherwise task-irrelevant distractors abolished the flanker effect. Like the load effect, the dilution effect is robust and has been replicated several times (Wilson et al., 2011; Benoni and Tsal, 2010, 2012).

The dilution alternative is incompatible with load theory; however, the current experiments are in line with both accounts. Although the current experiments were not designed to examine dilution some loose parallels can be drawn. It is entirely possible that dilution effects are experienced as *m*-Load. For instance, increments in display size may place demands on capacity restricted cognitive mechanisms like VSTM. When VSTM is loaded, the identity of the flanker becomes diluted in memory and thus fails to reach the response selection stage. How exactly dilution fits into this framework remains an open question, but acknowledging *m*-Load may provide an avenue to reconcile long-standing facets of load theory and the dilution account.

CONCLUSION

To explain attentional "spill-over" phenomena, load theory invokes unclear resources. We classified these resources into two categories: processing demands stemming from (1) the need to resolve feature-based competition, and (2) the need to readily encode fleeting visual representations. We proposed that whereas attentional resources satisfy the former condition, free mnemonic resources satisfy the latter. We introduced the term *m*-Load to describe task-imposed encoding restrictions and we presented a new account that reflects how *m*-Load interacts with conventional feature-based *p*-Load to produce the load effect. Lastly, we suggested that *m*-Load may prevent the flanker effect by denying the flanker's entry into VSTM. This contributes to the growing body of work on load theory and extends it to include two distinct classes of processing challenges set by the task environment.

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REFERENCES

Allport, D. A. (1977). On knowing the meaning of words we are unable to report: the effects of visual masking. *Attent. Perform.* 6, 505–533.

Averbach, E., and Coriell, A. S. (1961). Short-term memory in vision. *Bell Syst. Tech. J.* 40, 309–328. doi: 10.1002/j.1538-7305.1961.tb03987.x

Bavelier, D., Deruelle, C., and Proksch, J. (2000). Positive and negative compatibility effects. *Percept. Psychophys.* 62, 100–112. doi: 10.3758/BF03212064

Belopolsky, A. V., Kramer, A. F., and Godijn, R. (2008). Transfer of information into working memory during attentional capture. *Vis. Cogn.* 16, 409–418. doi: 10.1080/13506280701695454

Benoni, H., and Tsal, Y. (2010). Where have we gone wrong? Perceptual load does not affect selective attention. *Vis. Res.* 50, 1292–1298. doi: 10.1016/j.visres.2010.04.018

Benoni, H., and Tsal, Y. (2012). Controlling for dilution while manipulating load: perceptual and sensory limitations are just two aspects of task difficulty. *Psychon. Bull. Rev.* 19, 631–638. doi: 10.3758/s13423-012-0244-8

Benoni, H., and Tsal, Y. (2013). Conceptual and methodological concerns in the theory of perceptual load. *Front. Psychol.* 4:522. doi: 10.3389/fpsyg.2013.00522

Brainard, D. H. (1997). The psychophysics toolbox. *Spat. Vis.* 10, 433–436. doi: 10.1163/156856897X00357

Bundesen, C. (1990). A theory of visual attention. *Psychol. Rev.* 97, 523–547. doi: 10.1037/0033-295X.97.4.523

Bundesen, C., Habekost, T., and Kyllingsbæk, S. (2005). A neural theory of visual attention: bridging cognition and neurophysiology. *Psychol. Rev.* 112, 291. doi: 10.1037/0033-295X.112.2.291

Caparos, S., and Linnell, K. J. (2010). The spatial focus of attention is controlled at perceptual and cognitive levels. *J. Exp. Psychol. Hum. Percept. Perform.* 36, 1080. doi: 10.1037/a0020367

Cherry, E. C. (1953). Some experiments on the recognition of speech, with one and with two ears. *J. Acoust. Soc. Am.* 25, 975–979. doi: 10.1121/1.1907229

Coltheart, M. (1980). The persistences of vision. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* 290, 57–69. doi: 10.1098/rstb.1980.0082

Deutsch, J. A., and Deutsch, D. (1963). Attention: some theoretical considerations. *Psychol. Rev.* 70, 80. doi: 10.1037/h0039515

Di Lollo, V. (1980). Temporal integration in visual memory. *J. Exp. Psychol. Gen.* 109, 75–97. doi: 10.1037/0096-3445.109.1.75

Duncan, J. (1980). The locus of interference in the perception of simultaneous stimuli. *Psychol. Rev.* 87, 272–300. doi: 10.1037/0033-295X.87.3.272

Duncan, J., and Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychol. Rev.* 96, 433. doi: 10.1037/0033-295X.96.3.433

Elliott, J. C., and Giesbrecht, B. (2010). Perceptual load modulates the processing of distractors presented at task-irrelevant locations during the attentional blink. *Attent. Percept. Psychophys.* 72, 2106–2114. doi: 10.3758/APP.72.8.2106

Eriksen, B. A., and Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a non-search task. *Percept. Psychophys.* 16, 143–149. doi: 10.3758/BF03203267

Eriksen, C. W., and Hoffman, J. E. (1973). The extent of processing of noise elements during selective encoding from visual displays. *Percept. Psychophys.* 14, 155–160. doi: 10.3758/BF03198630

Gaspelin, N., Ruthruff, E., Jung, K., Cosman, J. D., and Vecera, S. P. (2012). Does low perceptual load enable capture by colour singletons? *J. Cogn. Psychol.* 24, 735–750. doi: 10.1080/20445911.2012.690553

Handy, T. C., and Mangun, G. R. (2000). Attention and spatial selection: electrophysiological evidence for modulation by perceptual load. *Percept. Psychophys.* 62, 175–186. doi: 10.3758/BF03212070

Hodsoll, S., Vinding E., and Lavie N. (2011). Attentional capture by irrelevant emotional distractor faces. *Emotion* 11, 346–353. doi: 10.1037/a0022771

Jolicœsur, P., and Dell'Acqua, R. (1998). The demonstration of short-term consolidation. *Cognit. Psychol.* 36, 138–202. doi: 10.1006/cogp.1998.0684

Jolicœsur, P., and Dell'Acqua, R. (1999). Attentional and structural constraints on visual encoding. *Psychol. Res.* 62, 154–164. doi: 10.1007/s004260050048

Klein, R. M., and Dukewich, K. (2006). Does the inspector have a memory? *Vis. Cogn.* 14, 648–667. doi: 10.1080/13506280500194022

Konstantinou, N., Bahrami, B., Rees, G., and Lavie, N. (2012). Visual short-term memory load reduces retinotopic cortex response to contrast. *J. Cogn. Neurosci.* 24, 2199–2210 doi: 10.1162/jocn_a_00279

Konstantinou, N., and Lavie, N. (2013). Dissociable roles of different types of working memory load in visual detection. *J. Exp. Psychol. Hum. Percept. Perform.* 39, 919–924. doi: 10.1037/a0033037

Kyllingsbæk, S., Sy, J. L., and Giesbrecht, B. (2011). Understanding the allocation of attention when faced with varying perceptual load in partial report: a computational approach. *Neuropsychologia* 49, 1487–1497. doi: 10.1016/j.neuropsychologia.2010.11.039

LaBerge, D. (1975). Acquisition of automatic processing in perceptual and associative learning. *Attent. Perform.* 5, 50–64.

Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. *J. Exp. Psychol. Hum. Percept. Perform.* 21, 451–468. doi: 10.1037/0096-1523.21.3.451

Lavie, N., and Cox, S. (1997). On the efficiency of selective visual attention: efficient visual serach leads to inefficient distractor rejection. *Psychol. Sci.* 8, 395–398. doi: 10.1111/j.1467-9280.1997.tb00432.x

Lavie, N., and de Fockert, J. (2003). Contrasting effects of sensory limits and capacity limits in visual selective attention. *Percept. Psychophys.* 65, 202–212. doi: 10.3758/BF03194795

Lavie, N., and de Fockert, J. (2005). The role of working memory in attentional capture. *Psychon. Bull. Rev.* 12, 669–674. doi: 10.3758/BF03196756

Lavie, N., and Fox, E. (2000). The role of perceptual load in negative priming. *J. Exp. Psychol. Hum. Percept. Perform.* 26, 1038–1052. doi: 10.1037/0096-1523.26.3.1038

Lavie, N., and Tsal, Y. (1994). Perceptual load as a major determinant of the locus of selection in visual attention. *Percept. Psychophys.* 56, 183–197. doi: 10.3758/BF03213897

Lien, M.-C., Ruthruff, E., and Johnston, J. C. (2010). Attentional capture with rapidly changing attentional control settings. *J. Exp. Psychol. Hum. Percept. Perform.* 36, 1–16. doi: 10.1037/a0015875

Loftus, G. R., and Masson, M. E. (1994). Using confidence intervals in within-subject designs. *Psychon. Bull. Rev.* 1, 476–490. doi: 10.3758/BF03210951

MacDonald, J. S., and Lavie, N. (2008). Load induced blindness. *J. Exp. Psychol. Hum. Percept. Perform.* 34, 1078. doi: 10.1037/0096-1523.34.5.1078

Miller, J. (1991). The flanker compatibility effect as a function of visual angle, attentional focus, visual transients, and perceptual load: a search for boundary conditions. *Percept. Psychophys.* 49, 270–288. doi: 10.3758/BF03214311

Morey, R. D. (2008). Confidence intervals from normalized data: a correction to Cousineau (2005). *Tutor. Quant. Methods Psychol.* 4, 61–64.

Most, S. B., Smith S. D., Cooter A. B., Levy B. N., and Zald D. H. (2007). The naked truth: positive, arousing distractors impair rapid target perception. *Cognit. Emot.* 21, 964–981. doi: 10.1080/02699930600959340

Neisser, U. (1969). "Selective reading: a method for the study of visual attention," in *19th International Congress of Psychology*, London.

Norman, D. A., and Bobrow, D. G. (1975). On data-limited and resource-limited processes. *Cognit. Psychol.* 7, 44–64. doi: 10.1016/0010-0285(75)90004-3

Phillips, W. A. (1974). On the distinction between sensory storage and short-term visual memory. *Attent. Percept. Psychophys.* 16, 283–290. doi: 10.3758/BF03203943

Potter, M. C. (1976). Short-term conceptual memory for pictures. *J. Exp. Psychol. Hum. Learn. Mem.* 2, 509–522. doi: 10.1037/0278-7393.2.5.509

Pratt, J., and McAuliffe, J. (2001). The effects of onsets and offsets on visual attention. *Psychol. Res.* 65, 185–191. doi: 10.1007/s004260100058

Roper, Z. J. J., Cosman, J. D., Mordkoff, J. T., and Vecera, S. P. (2011). Perceptual load effect is determined by resource demand and data limitation. *J. Vis.* 11, 247. doi: 10.1167/11.11.247

Roper, Z. J. J., Cosman, J. D., and Vecera, S. P. (2013). Perceptual load corresponds to factors known to influence visual search. *J. Exp. Psychol. Hum. Percept. Perform.* 39, 1340–1351. doi: 10.1037/a0031616

Roper, Z. J. J., and Vecera, S. P. (2013). Visual short-term memory strengthens selective attention. *Psychon. Bull. Rev.* doi: 10.3758/s13423-013-0503-3 [Epub ahead of print].

Schmidt, B. K., Vogel, E. K., Woodman, G. F., and Luck, S. J. (2002). Voluntary and automatic attentional control of visual working memory. *Attent. Percept. Psychophys.* 64, 754–763. doi: 10.3758/BF03194742

Sperling, G. (1960). The information available in brief visual presentations. *Psychol. Monogr. Gen. Appl.* 74, 498–526.

Torralbo, A., and Beck, D. M. (2008). Perceptual-load-induced selection as a result of local competitive interactions in visual cortex. *Psychol. Sci.* 19, 1045–1050. doi: 10.1111/j.1467-9280.2008.02197.x

Treisman, A. M. (1969). Strategies and models of selective attention. *Psychol. Rev.* 76, 282. doi: 10.1037/h0027242

Tsal, Y., and Benoni, H. (2010). Diluting the burden of load: perceptual load effects are simply dilution effects. *J. Exp. Psychol. Hum. Percept. Perform.* 36, 1645. doi: 10.1037/a0018172

Vogel, E. K., Luck, S. J., and Shapiro, K. L. (1998). Electrophysiological evidence for a postperceptual locus of suppression during the attentional blink. *J. Exp. Psychol. Hum. Percept. Perform.* 24, 1656. doi: 10.1037/0096-1523.24.6.1656

Wilson, D. E., Muroi, M., and MacLeod, C. M. (2011). Dilution, not load, affects distractor processing. *J. Exp. Psychol. Hum. Percept. Perform.* 37, 319. doi: 10.1037/a0021433

Yantis, S., and Johnston, J. C. (1990). On the locus of visual selection: evidence from focused attention tasks. *J. Exp. Psychol. Hum. Percept. Perform.* 16, 135–149. doi: 10.1037/0096-1523.16.1.135

Zhang, W., and Luck, S. J. (2008). Discrete fixed-resolution representations in visual working memory. *Nature* 453, 233–235. doi: 10.1038/nature06860

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Degraded stimulus visibility and the effects of perceptual load on distractor interference

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In this study we examined whether effects of perceptual load on the attentional selectivity are modulated by degradation of the visual input. According to the perceptual load theory, increasing task difficulty via degradation of stimulus visibility should not alter the typical effect of perceptual load. In previous studies only the target was degraded, resulting in increased distractor saliency. Here we combined manipulation of perceptual load with a more systematic degradation of visual information. Experiment 1 included five conditions. Three conditions involved low perceptual load + contrast reduction of: (A) only the target; (B) only the distractor; (C) both target and distractor. The other two conditions included non-degraded stimuli with low or high perceptual load. In Experiment 2 visibility degradation was established via manipulation of exposure duration. It included two exposure durations—100 and 150 ms—for each load level (low vs. high). The results of both experiments demonstrated reliable distractor interference of a similar magnitude with both degraded and non-degraded stimuli. This finding suggests that task difficulty, when manipulated via degradation of stimulus visibility, does not play a critical role in determining the efficiency of the attentional selectivity. However, contrary to the predictions of the perceptual load theory, in both experiments distractor interference emerged under the high load condition. In Experiment 2 the high-load interference was of the same magnitude as that of the low load condition. This high-load interference is not due to the presence of a mask (Experiment 3) or a mixed design (Experiment 4). These findings suggest that perceptual load may also play a lesser role in attentional selectivity than that assigned to it by the perceptual load theory.

Keywords: perceptual load, stimulus visibility, attentional selectivity, distractor interference, task difficulty, sensory load

INTRODUCTION

The perceptual load theory (e.g., Lavie, 1995; Lavie and Cox, 1997; Maylor and Lavie, 1998) offers a theoretical account for the fact that in some cases the attentional selectivity seems too high (e.g., Mack and Rock, 1998; Mack et al., 2002), while in other cases the attentional selectivity seems too low (e.g., Eriksen and Eriksen, 1974; Theeuwes, 1992). It suggests that perceptual load, defined as the need to carry out further perceptual operations or apply the same operation to additional units, is the critical factor that determines the extent to which non-attended information is processed. According to the theory, as long as capacity limitations were not met, perceptual processing proceeds automatically on all stimuli, relevant or not. Once the capacity exceeds its limitations, irrelevant information can no longer be processed. When the relevant information imposes a high load it exhausts the available processing capacity and in turn the processing of irrelevant information is prevented. To support the theory, Lavie and Cox (1997) varied the load by changing the similarity between a target and non-target letters and the heterogeneity of the non-target letters. The target, "N" or "X," was presented in one of six positions on an imaginary circle. The other five positions were occupied by either other heterogeneous letters (H, M, K, Z, W) in the high perceptual load condition, or by five homogeneous "O's" in the low perceptual load condition. The task was to indicate whether there was an X or an N in the circle of letters while ignoring a peripheral distractor letter. The distractor was either compatible with the target, incompatible or neutral. A compatibility effect—incompatible reaction time (RT) minus neutral RT—was found in the low load condition but was absent in the high load condition. Hence, in accordance with the perceptual load theory, the low load condition resulted in an inefficient filtering out of distractors, while the high load condition resulted in an efficient filtering out of distractors. Similar results were found with different stimuli and manipulations of perceptual load (e.g., Handy et al., 2001; Lavie and Robertson, 2001; Bahrami et al., 2007; Brand-D'Abrescia and Lavie, 2007; Rorden et al., 2008; but see Khetrapal, 2010; Tsal and Benoni, 2010; Marciano and Yeshurun, 2011).

In this study we tested whether degrading the quality of the visual input will modulate these effects of perceptual load, as defined above by the perceptual load theory. One possible alternative explanation of previous findings suggests that the lack of compatibility effect in the high load condition is not due to the exhaustion of processing resources brought about by the high levels of load but simply to the fact that the task in this condition is considerably more difficult than that in the low load condition.

Lavie and de Fockert's (2003) study was designed to disprove this alternative explanation. They based their rationale on the assumption that perceptual load is different from sensory limits. This assumption was inspired by Norman and Bobrow's (1975) distinction between data-limited and resource-limited processes. Data limits refer to limitation on the quality of the input while resource limits refer to limitation on resources available for the processing of the input. Applying more resources may not overcome data limitation. As mentioned above, according to the perceptual load theory, perceptual load can be operationalized in two different ways: either additional perceptual operations must be carried out (e.g., the processing of a target defined by feature vs. the processing of a target defined by a conjunction of features), or the same operations must be applied to more items (e.g., a manipulation of set size). The argument of the perceptual load theory is that the additional operations or items in the high load condition consume attentional capacity, thereby preventing the processing of the irrelevant information. However, making the task harder by increasing data limits without increasing perceptual load (as defined above) should not consume attentional capacity and therefore the irrelevant distractor should be processed and interference should be found. Thus, manipulating the sensory limits via degradation of target visibility (i.e., degrading the quality of the input) should increase general task difficulty but should not impose additional demands on the attentional resources, leaving available capacity for distractor processing. To test this hypothesis they compared the effects of perceptual load on distractor interference with the effects of various manipulations of sensory degradation of the target stimulus. They employed three manipulations of target degradation that involved three different combinations of the following: decreasing the size and contrast of the target, shortening the exposure duration, presenting masks after the target display that mask the target, and increasing the eccentricity of the target. The results of these experiments showed that although degrading the quality of the sensory input of the target increased RT, indicating that the degradation manipulation increased task difficulty, it did not reduce the interference of the irrelevant distractor. Irrelevant distractor interference was found in all the degraded target conditions and it was even greater than the interference in the non-degraded low load conditions. Such interference was not found in the conditions of high perceptual load. According to Lavie and de Fockert (2003), this pattern of results suggests that merely impairing the sensory input of a target stimulus is not equal to overloading the perceptual process. To load the perceptual processes one should add perceptual operations or more items to the task. Thus, Lavie and de Fockert concluded that while perceptual load decreases distractor interference, sensory degradation increases it.

However, Lavie and de Fockert (2003) only degraded the target. That is, only the target contrast and size was reduced; only the target positions were masked—there were no masks at the distractor positions; and only the target eccentricity was increased. Because the distractor in their study was not degraded at all, target degradation might have rendered the target less conspicuous in comparison to the distractor. It is possible, therefore, that the processing of the degraded target did require more resources but because the distractor was more conspicuous it nevertheless interfered with the response to the target (either because fewer processing resources were needed for it to cause interference due to its higher conspicuity, or because its conspicuity captured attention away from the target). If so, the assumption that perceptual load is different from sensory limits does not hold. The goal of the current study was to test in a more comprehensive way the effect that degrading the quality of the visual input may have on distractor interference. To that end, we combined manipulation of perceptual load with degradation of visual information in both relevant and irrelevant regions of the visual field. Specifically, in Experiment 1, we employed a similar load manipulation to that of Lavie and de Fockert and added three different conditions of degradation: (A) contrast reduction of both the target and distractor stimuli; (B) contrast reduction of the target stimuli alone; and (C) contrast reduction of the distractor stimuli alone. All three conditions involved low levels of load, and distractor interference under these degraded conditions was compared to that with two non-degraded conditions—one with low levels of load and the other with high levels of load. Experiment 2 included a load manipulation that is similar to that of Lavie and Cox (1997), and a different manipulation of visibility degradation. Specifically, we shortened the exposure duration of all the stimuli and compared this degraded condition with a condition that included the typical exposure duration. All possible target and distractor positions were masked. To foreshadow the results of both experiments, we found reliable distractor interference regardless of degradation manipulation. However, in contrast to the predictions of the perceptual load theory, reliable distractor interference was also observed in the high load condition. Experiments 3, 4 explored possible explanations for this latter finding.

EXPERIMENT 1

In this experiment we extended the degradation manipulation to also include non-relevant locations. To degrade the quality of the visual input we lowered the contrast of the stimuli in three different degradation conditions: (1) the contrast of both target and distractor was reduced; (2) the contrast of the target was reduced but not that of the distractor. This condition is similar to Lavie and de Fockert (2003); and (3) the contrast of the distractor was reduced but not that of the target. These degraded conditions involved low levels of perceptual load, and distractor interference (i.e., compatibility effect) in these conditions was compared to that of a fourth low load condition with the contrast of both target and distractor intact. Finally a fifth condition included high levels of perceptual load without degradation. The last two conditions were also included in Lavie and de Fockert's study. The load manipulation was based on that of Lavie and de Fockert. The target letter (N or X) was presented on an imaginary circle in one of eight possible locations. In the low load conditions there were no other non-target letters in the circle while in the high load condition the target was presented together with seven non-target letters (G, H, J, P, S, U, Y). All these different conditions are presented in **Figure 1**. If Lavie and de Fockert's findings were not merely due to the fact that only the target was degraded, the following results are expected: All low load conditions should result

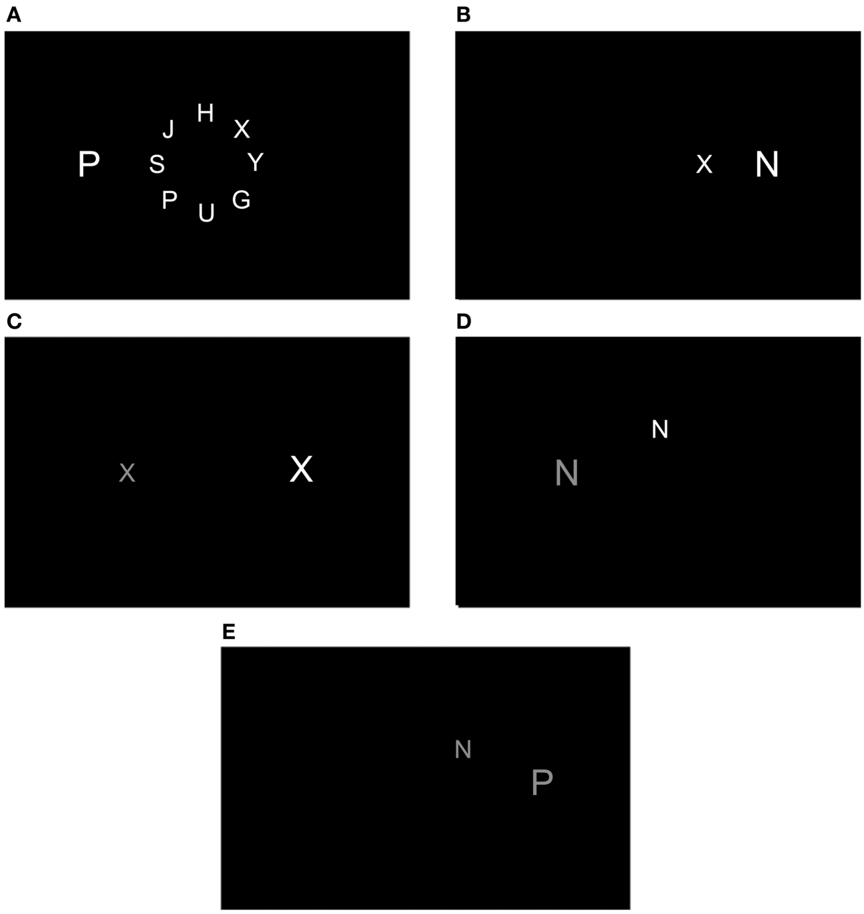

FIGURE 1 | The various conditions of Experiment 1: (A) High load, no degradation (HLND); (B) Low load, no degradation (LLND); (C) Low load, target degradation (LLTD); (D) Low load, distractor degradation (LLDD); (E) Low load, both target and distractor degradation (LLBD).

in considerable distractor interference with a larger interference in the degraded than non-degraded conditions, at least when only the target is degraded. There should be no distractor interference in the high load condition or at least the interference in this condition should be considerably smaller.

MATERIALS AND METHODS

Participants

Eighteen naive observers, from the University of Haifa, with normal or corrected to normal vision participated in Experiment 1.

Stimuli

The target letter was an N or an X, presented in one of eight evenly spaced locations on an imaginary circle of letters (1.3° radius; 0.95° center to center distance of neighboring locations). The target was either presented together with other seven letters (G, H, J, P, S, U, Y) in the high-load-no-degradation (HLND) condition, or presented alone in all the other experimental conditions (**Figure 1**). The height and width of the letters on the circle were 0.6° × 0.4° of visual angle. The distractor letter was presented to the right or left of the imaginary circle, and its height and width were increased (1.0° × 0.55°) to control for the effect of eccentricity (Maylor and Lavie, 1998). The distractor was placed at an eccentricity of 3.2°. On one third of the trials the distractor was incompatible with the target (e.g., the target was the letter N and the distractor was the letter X); on another third of the trials the distractor was compatible with the target (e.g., both were the letter N); and on the rest of the trials the distractor was neutral (the letter P). The target and the distractor appeared equally often at each of their possible locations. In all conditions the letters were gray and the background was black (background luminance: 0.4 cd/m^2). In the HLND and low-load-no-degradation (LLND) conditions the luminance of all the stimuli was 18.3 cd/m^2. In the low-load-target-degraded (LLTD) condition the luminance of the target was 2 cd/m^2 while the luminance of the distractor was 18.3 cd/m^2. In the low-load-distractor-degraded (LLDD) condition the luminance of the distractor was 2 cd/m^2 while the luminance of the target was 18.3 cd/m^2. In the low-load-both-degraded (LLBD) condition the luminance of both target and distractor was 2 cd/m^2.

Procedure

The experiment took place in a dark room. Viewing distance was held fixed at 57 cm with a chin-rest. The task was to indicate as quickly and accurately as possible whether the target letter in the circle of letters was an X or an N (by clicking the N or the X keys), while ignoring the distractor. Each trial started with a 1000 ms fixation mark presented in the middle of the screen. To prevent eye movements, the letters display followed for a short duration of 150 ms (e.g., Mayfrank et al., 1987), and was replaced by a blank screen until the participant responded but no longer than 3000 ms (**Figure 2**). After responding, a 500 ms feedback was given: a "+" sign for a correct response, and a "−" sign for an incorrect response.

Each of the five different conditions (HLND, LLND, LLTD, LLDD, and LLBD) was presented in three different successive blocks of 96 trials each (total of 288 trials for each load-degradation condition, 96 for each compatibility condition). The presentation order of the five conditions was randomly chosen for each participant. Each participant viewed a total of 1440 experimental trials that were preceded by 30 practice trials.

RESULTS AND DISCUSSION

The first block of each load-degradation condition served as practice and was excluded from the analysis. To take into consideration both accuracy and RT we calculated inverse efficiency (IE) scores by dividing the mean correct RT, for each condition of each participant, by the corresponding proportion correct (e.g., Townsend and Ashby, 1983). RTs shorter than 100 ms or longer than 2000 ms—0.18% from the total number of correct trials—were excluded from the calculation of mean RT. Like RT, higher IE scores indicate worse performance. In fact, IE scores are often referred to as "corrected RT" because they are considered as a measure of performance that circumvents possible criterion shifts or speed-accuracy tradeoffs (e.g., Townsend and Ashby, 1983; Murphy and Klein, 1998; Spence et al., 2001; Roder et al., 2007; Collignon et al., 2008). **Table 1** presents the mean correct RT, accuracy (% correct) and IE scores for the various load-degradation and compatibility conditions. A two-way repeated measures ANOVA, load-degradation condition (HLND, LLND, LLBD, LLTD, or LLDD) × compatibility (neutral, incompatible, or compatible) was conducted on the IE scores[1]. The main effect of load-degradation condition was significant [$F_{(4, 68)} = 20.03$, $p < 0.0001$]. As can be seen in **Figure 3** and **Table 1**, and confirmed by least significant differences (LSD) *post-hoc* analysis,

[1]The same analysis was performed separately on mean correct RT and accuracy. In all the experiments reported here, these separate analyses and the analysis of IE scores lead to similar conclusions. The RT and accuracy analyses are provided as supplementary material.

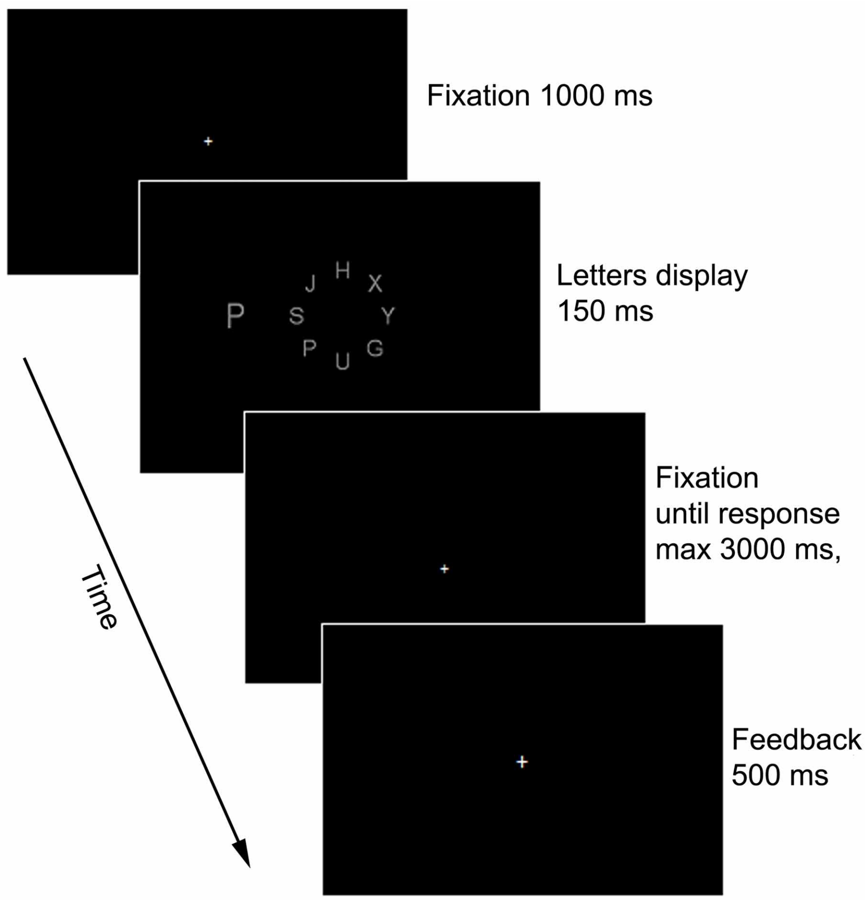

FIGURE 2 | A schematic illustration of a single trial in Experiment 1.

Table 1 | Mean correct RT, accuracy and IE scores (inverse efficiency = RT/accuracy) as a function of load-degradation and compatibility conditions in Experiment 1.

Load-degradation condition	*RT* (ms) Distractor compatibility				Accuracy (%) Distractor compatibility				*IE* scores Distractor compatibility			
	IC	*C*	*N*	Total	*IC*	*C*	*N*	Total	*IC*	*C*	*N*	Total
HLND	542	538	537	539	92.4	93.6	95.1	93.7	588	577	567	577
LLND	466	424	427	439	90.3	94.9	95.5	93.6	518	447	449	471
LLBD	549	492	492	511	90.2	95.5	92.7	92.8	615	518	534	556
LLTD	552	500	514	522	87.6	94.5	93.3	91.8	634	529	552	572
LLDD	400	381	382	388	93.7	94.7	95.4	94.6	428	403	401	411
Total	502	467	471		90.8	94.6	94.4		557	495	501	

IC, incompatible condition; C, compatible condition; N, neutral condition.

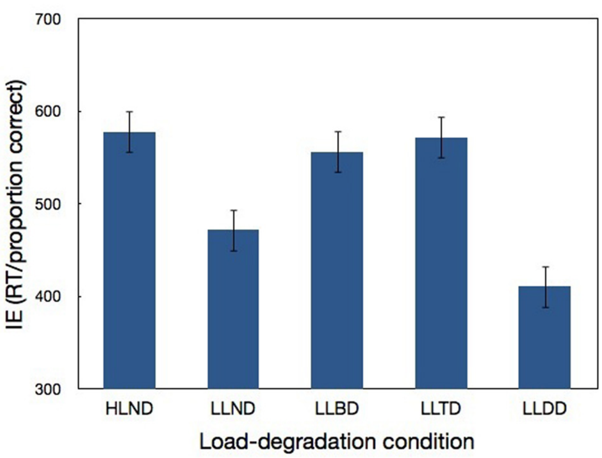

FIGURE 3 | Participants' IE scores (inverse efficiency: RT/proportion correct) in Experiment 1 as a function of load-degradation condition. Error bars correspond to 1 SE.

performance in the non-degraded low-load condition (LLND) was significantly better (smaller IE scores; $p < 0.0001$) than in the high-load condition (HLND). This confirms that the manipulation of load was successful. The degradation manipulation was also successful, as decreasing the contrast of the target, either by itself (LLTD) or with the distractor (LLBD) resulted in a significantly worse performance ($p < 0.0006$) than when the target was not degraded (LLND, LLDD). Interestingly, a significant difference was also found between LLND and LLDD (i.e., worse performance when there was no degradation than when only the distractor was degraded; $p < 0.02$). This finding suggests that the conspicuity of the target relative to the distractor is indeed an important factor because when the relative conspicuity of the target was increased by decreasing only the contrast of the distractor, performance improved. The main effect of compatibility was also significant [$F_{(2, 34)} = 63.68$, $p < 0.0001$]. LSD *post-hoc* analysis indicated that performance in the incompatible condition was significantly worse than in either the neutral condition ($p < 0.0001$) or the compatible condition ($p < 0.0001$).

Importantly, the two-way interaction between load-degradation condition and compatibility was significant [$F_{(8, 136)} = 6.55$, $p < 0.0001$]. **Figure 4** shows that a significant distractor interference (incompatible—neutral) was found in all low load conditions (LLND, LLBD, LLTD: $p < 0.0001$; LLDD: $p < 0.03$). The fact that significant distractor interference was found in all the low load conditions regardless of degradation is in agreement with the perceptual load theory and with Lavie and de Fockert's (2003) claim that the degree of distractor interference does not depend on task difficulty. However, unlike Lavie and de Fockert's study, distractor interference in the target-degraded condition (LLTD) was not significantly higher than distractor interference in the non-degraded condition (LLND). Additionally, the interference effect in the LLBD and LLDD conditions indicates that the distractor was perceivable even when it was degraded, and the significantly larger interference in the LLTD than LLDD ($p < 0.006$) suggests that the conspicuity of the target relative to the distractor is important, because the interference was larger when the distractor was more conspicuous (LLTD) than when the target was more conspicuous (LLDD).

A marginally significant distractor interference ($p = 0.081$) was also found in the high-load condition (HLND). This interference is not consistent with the predictions of the perceptual load theory under the assumption that with high levels of load all the attentional resources were consumed by the central task. However, if the processing of central information with high levels of load did not consume all available resources, then the theory predicts some interference in the high load condition, though smaller than in the low load conditions. Indeed, the interference in the HLND condition was significantly smaller than in the LLND condition ($p < 0.02$) and LLTD and LLBD conditions ($p < 0.003$) but not LLDD condition. As for distractor facilitation (compatible—neutral), only a marginally significant effect ($p = 0.057$) was found in one condition—LLTD. This is consistent with Lavie's (1995) claim that the compatible condition is not optimally suited to explore the issue of distractor processing.

To sum, like the study of Lavie and de Fockert (2003) distractor interference was found even when the quality of the visual input was degraded. However, unlike their study degrading the target did not increase distractor interference. Interestingly, although distractor interference was found with degraded distractors, suggesting that the distractor was processed to a sufficient level, the interference was smallest when only the distractor was degraded (i.e., in comparison to the other low load conditions). Moreover, distractor interference was significantly larger when the distractor was more conspicuous in comparison to the target (LLTD) than when the target was more conspicuous in comparison to the distractor (LLDD). This finding suggests that the relative conspicuity of the target does play a role in determining the efficiency of the attentional selectivity. Finally, a marginally significant distractor interference was also found in the high load condition. This interference was smaller than the low load condition.

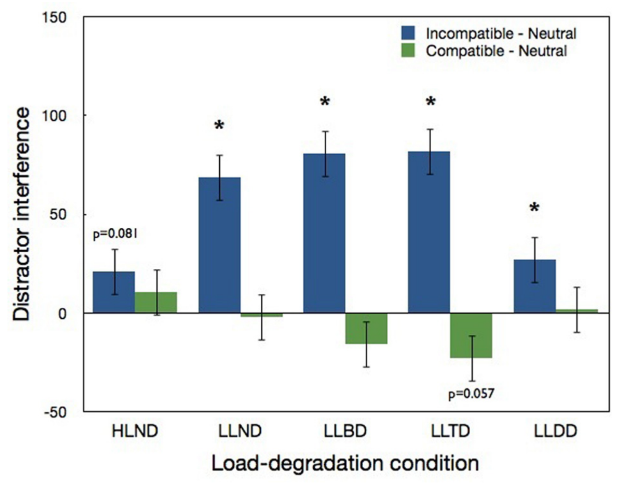

FIGURE 4 | Distractor interference (incompatible minus neutral) and distractor facilitation (compatible minus neutral) in Experiment 1 as a function of load-degradation condition. "∗" indicates a significant effect of the simple pairwise comparisons with neutral conditions. Error bars correspond to 1 SE.

EXPERIMENT 2

This experiment tested whether similar results will emerge with a different manipulation of stimulus degradation and perceptual load. The degradation manipulation employed here involved exposure duration. Thus, the contrast of all the various stimuli was the same but in the degraded conditions the exposure duration of the stimuli was considerably shortened. Specifically, this experiment included two exposure duration conditions: a non-degraded condition in which exposure duration was 150 ms, and a degraded condition in which exposure duration was shortened to 100 ms. Each of these conditions included further manipulation of load and compatibility. The manipulation of compatibility was identical to that of Experiment 1, but the manipulation of load was different. In Experiment 1 perceptual load was manipulated by varying the set-size. Here, perceptual load was manipulated by changing the similarity between a target and non-target letters and the heterogeneity of the non-target letters (e.g., Lavie and Cox, 1997; Marciano and Yeshurun, 2011). In the low load condition, the imaginary circle included, in addition to the target, five homogeneous O's (**Figure 5**) while in the high load condition the other non-target letters were heterogeneous and shared features with the target (X, K, H, Y, V). If, as Lavie and de Fockert (2003) claim, perceptual load decreases distractor interference while sensory degradation increases it, then distractor interference should only be found with the low load conditions (or at least be larger than in the high load conditions), and a larger distractor interference should be found with the shorter exposure duration condition.

MATERIALS AND METHODS

Participants

Twenty-four students from the University of Haifa took part in this experiment for monetary reward or course credit. All had normal or corrected to normal vision and all were naive to the purpose of the study. None of them participated in Experiment 1.

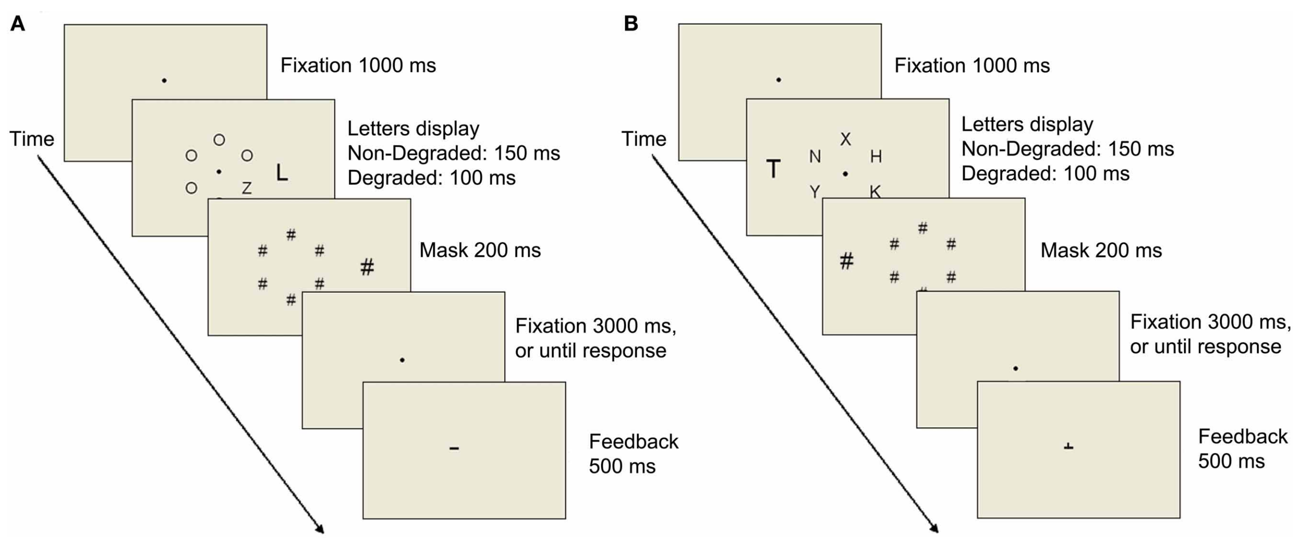

FIGURE 5 | A schematic illustration of a single trial in Experiment 2 with (A) low load display (B) high load display.

Stimuli

The stimuli of this experiment were similar to Experiment 1 except for the following: The target letter was either an N or a Z. Accordingly, in the compatible and incompatible conditions the distractor letter was also either an N or a Z. In the neutral condition the distractor was either an L or a T. There were only six possible locations on the imaginary circle of letters (2° radius; 1.7° center to center distance of neighboring locations). The target appeared equally often at each of the six possible locations. The other five letters were either all O's in the low load conditions or X, K, H, Y, and V in the high load conditions (**Figure 5**). The distractor was placed at an eccentricity of 4°. All the letters were black presented on a light gray background. The mask was composed of seven black # symbols located at each of the seven letters positions (six positions in the circle of letters and one position of the distractor letter). The size of the # symbol was identical to the size of the letter it masked (i.e., the # symbol that masked the distractor was larger).

Procedure

The procedure of this experiment was similar to Experiment 1 except for the following: The letters display was presented for a duration of 150 ms in the non-degraded condition and 100 ms in the degraded condition. The mask followed the letters display, and it was presented for 200 ms. Each block included 144 trials divided equally between the two exposure duration conditions (100 and 150 ms), and between the three compatibility conditions (compatible, incompatible, and neutral). The different exposure duration trials and the different compatibility trials were presented in random order within each block. The load conditions (low load and high load) were blocked. Similar to Forster and Lavie (2007), the order of the load blocks was fixed for all participants: low, high, low, high, high, low, low, high, high, low. Each participant performed 1440 trials, 720 of each exposure duration condition and 480 of each condition of load.

RESULTS AND DISCUSSION

The first two blocks served as practice and were excluded from the analysis. As in Experiment 1, we calculated IE scores for each condition of each participant, with the same RT exclusion criterion (excluding 0.29% from the total number of correct trials). These IE scores were submitted to a three-way repeated measures ANOVA, load (low vs. high) x exposure duration (150 vs. 100 ms) × compatibility (neutral, incompatible, or compatible). The means of RT, accuracy and IE scores for all the conditions are presented in **Table 2**. All three main effects were significant: performance was better (smaller IE scores) with low than high load levels [$F_{(1, 23)} = 108.93$, $p < 0.0001$], longer than shorter exposure durations [$F_{(1, 23)} = 29.09$, $p < 0.0001$], and was best in the compatible condition and worst in the incompatible condition [$F_{(2, 46)} = 39.47$, $p < 0.0001$]. Thus, the manipulations of load and degradation employed in this experiment were successful. The two-way interaction between compatibility and exposure duration was also significant [$F_{(2, 46)} = 4.66$, $p < 0.02$]. LSD *post-hoc* analysis indicated that distractor interference (incompatible—neutral) was significant in both exposure durations ($p < 0.0001$), yet it was larger with the 100 ms than 150 ms duration.

The three-way interaction between load, exposure duration, and compatibility was not significant. Nevertheless, LSD *post-hoc* analysis was performed because of its theoretical importance. As can be seen in **Figure 6** and **Table 2**, in the low load conditions significant distractor interference was found in both 150 and 100 ms duration ($p < 0.0002$). Thus, as predicted based on Lavie and de Fockert (2003), increasing task difficulty by reducing the exposure duration did not eliminate the interference induced by the incompatible distractor. Also in accordance with Lavie and de Fockert, the magnitude of the interference was larger with marginal significance ($p = 0.095$) in the degraded 100 ms condition than in the non-degraded 150 ms condition. Notwithstanding the confirmation of Lavie and de Fockert's assertion regarding distractor interference and task difficulty, the basic prediction of the perceptual load theory was not confirmed because with both exposure durations significant distractor interference was found in the high load condition ($p < 0.0001$). Moreover, this high load interference was not smaller in magnitude, as may be expected according to the perceptual load theory. Indeed, the magnitude of the distractor interference in the high load condition of the 150 ms duration did not differ significantly from the interference of the corresponding low load condition, and was in fact larger ($p < 0.02$) in the high than low load conditions of the 100 ms duration. Regarding distractor facilitation (compatible—neutral), a significant difference ($p < 0.04$) was found for all the

Table 2 | Mean correct RT, accuracy and IE scores (inverse efficiency = RT/accuracy) as a function of load-degradation and compatibility conditions in Experiment 2.

Load-degradation condition	*RT* (ms) Distractor compatibility				Accuracy (%) Distractor compatibility				*IE* scores Distractor compatibility			
	IC	*C*	*N*	Total	*IC*	*C*	*N*	Total	*IC*	*C*	*N*	Total
Low load 100	624	600	608	611	83.4	91.9	89.1	88.1	762	659	688	703
High load 100	665	674	676	672	65.1	75.6	74.8	71.8	1033	904	917	951
Low load 150	611	578	600	596	87.4	92.7	91.6	90.6	704	629	658	664
High load 150	701	694	699	698	72.3	79.1	78	76.5	982	889	913	928
Total	650	637	646		77.1	84.8	83.3		870	770	794	

IC, incompatible condition; C, compatible condition; N, neutral condition.

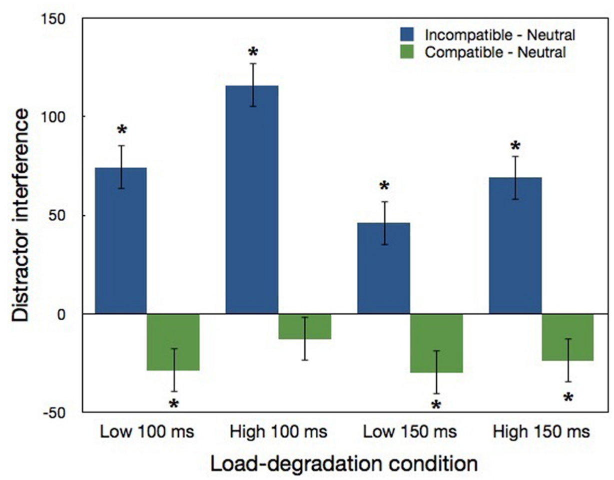

FIGURE 6 | Distractor interference (incompatible minus neutral) and distractor facilitation (compatible minus neutral) in Experiment 2 as a function load-degradation condition. "∗" indicates a significant effect of the simple pairwise comparisons with neutral conditions. Error bars correspond to 1 SE.

load-degradation conditions apart from the high load 100 ms condition.

To sum, like the study of Lavie and de Fockert (2003) and Experiment 1 of this study, distractor interference was found even when the quality of the visual input was degraded. Additionally, degrading the display resulted in larger distractor interference that was marginally significant. A significant distractor interference was found in the high load conditions. This is similar to Experiment 1 in which a marginally significant high load interference emerged, however in the current experiment this interference was not smaller than the interference of the low load condition with 150 ms duration and even larger with the 100 ms duration. Thus, these results are not in line even with the weaker version of the perceptual load theory that allows for a smaller interference with high levels of load. This unexpected distractor interference is further explored in Experiments 3, 4.

EXPERIMENT 3

The stimuli and procedure of Experiment 2 (particularly the 150 ms condition) were very similar to Experiment 4 in a previous study of ours (Marciano and Yeshurun, 2011). Still, in that experiment no interference was found in the high load condition while in Experiment 2 of this study we found such high-load distractor interference that was similar or even larger than the low-load interference. One methodological difference that might have led to this discrepancy is the presence of masks in Experiment 2. That is, in Experiment 2 masks followed the letter display with both exposure durations, but in Experiment 4 of Marciano and Yeshurun's study, which only included exposure duration of 150 ms, there was no such backward masking. The mask was added in Experiment 2 because the main degradation manipulation in that experiment was exposure duration shortening, and a mask is required to ensure brief presentation. Could the addition of a mask explain the emergence of distractor interference with high levels of load?

According to the perceptual load theory the addition of a mask should not have mattered—there should be no distractor interference (or a smaller interference) in the high load condition regardless of the presence or absence of a mask. This is because according to the theory the attentional selection is strictly passive, stemming from the exhaustion of the available processing capacity imposed by the higher perceptual load. The addition of a mask after the offset of the letter display should not affect the availability of resources, and therefore should not affect the magnitude of distractor interference. In contrast, with a more active view of the attentional selectivity, in which the lack of distractor interference reflects an active inhibition, the mask might matter if we assume that this inhibition requires time to exert its effect. When the stimuli are masked there might not be enough time to develop full inhibition and distractor interference emerges. This explanation gains some support from the fact that distractor interference in the shorter (100 ms) high load condition of Experiment 2 was significantly larger ($p < 0.005$) than that of the longer (150 ms) high load condition. Hence, when there was less time for inhibition to evolve a larger interference was observed. If indeed the emergence of distractor interference with high load levels is due to the presence of the mask, then once the mask is removed the interference should disappear or at least decrease considerably. To test this prediction, this experiment was identical to Experiment 2 apart from not including backward masking.

MATERIALS AND METHODS

Participants

Eighteen students from the University of Haifa took part in this experiment for monetary reward or course credit. All had normal or corrected to normal vision and all were naive to the purpose of the study. None of them participated in the previous experiments.

Stimuli and procedure

The stimuli and procedure of this experiment were identical to Experiment 2 except for the fact that a mask did not follow the letter display.

RESULTS AND DISCUSSION

As in previous experiments, we calculated IE scores for each condition of each participant, with the same RT exclusion criterion (excluding 0.21% from the total number of correct trials, after the exclusion of the first two blocks that served as practice). These IE scores were submitted to a three-way repeated measures ANOVA, load (low vs. high) × exposure duration (150 vs. 100 ms) × compatibility (neutral, incompatible, or compatible). The means of RT, accuracy and IE scores for all the conditions are presented in **Table 3**. The main effect of load was significant [$F_{(1, 17)} = 81.16$, $p < 0.0001$]; poorer performance (larger IE scores) were found with high than low load conditions. The main effect of compatibility was also significant [$F_{(2, 34)} = 107.93$, $p < 0.0001$]. Performance was best in the compatible condition and worst in the incompatible condition. The main effect of exposure duration was not significant ($p = 0.58$), suggesting that without a backward mask the manipulation of exposure duration is not effective.

Table 3 | Mean correct RT, accuracy and IE scores (inverse efficiency = RT/accuracy) as a function of load-degradation and compatibility conditions in Experiment 3.

Load-degradation condition	*RT* (ms) Distractor compatibility				Accuracy (%) Distractor compatibility				*IE* scores Distractor compatibility			
	IC	*C*	*N*	Total	*IC*	*C*	*N*	Total	*IC*	*C*	*N*	Total
Low load 100	612	567	574	584	93.3	95.7	95.9	95	656	594	599	616
High load 100	726	710	713	716	86.9	91.2	89.9	89.4	841	782	797	807
Low load 150	607	569	581	586	94.4	96.8	96.1	95.8	642	589	605	612
High load 150	735	712	709	719	87.3	90.9	90.3	89.5	846	787	789	807
Total	670	640	644		90.5	93.7	93.1		746	688	698	

IC, incompatible condition; C, compatible condition; N, neutral condition.

The three-way interaction between load, exposure duration and compatibility was not significant, still LSD *post-hoc* comparisons were analyzed due to their theoretical importance. As can be seen in **Figure 7**, in the low load conditions distractor interference was significant in both the 100 ms condition ($p < 0.0001$), and the 150 ms condition ($p < 0.0004$). As in our previous experiments, the significant distractor interference found in the harder low load condition (i.e., 100 ms exposure duration) is consistent with Lavie and de Fockert's (2003) claim that task difficulty *per se* is not the reason for the lack of interference with high levels of load. Also similar to Experiment 1, the interference in the 100 ms low load condition was not significantly larger than in the 150 ms low load condition. Finally, in contrast to the predictions of the perceptual load theory but similar to our previous experiments, significant distractor interference also emerged in the high load conditions ($p < 0.0001$), and with both duration conditions the magnitude of the interference did not differ significantly in the high vs. low load conditions. Thus, the observed high load interference was not smaller in magnitude, as may be expected according to the weaker version of the perceptual load theory. Regarding distractor facilitation, a marginally significant difference ($p = 0.083$) was found only for the low load 150 ms condition.

To sum, this experiment replicated the main findings of our two previous experiments: shortening the exposure duration did not decrease distractor interference but also did not increase it. However, unlike Experiment 2, the two exposure duration conditions did not differ significantly, suggesting that without a backward mask the manipulation of degradation via shortening of exposure duration is not effective. Importantly, the goal of this experiment was not to test whether the manipulation of exposure duration without a backward mask is an effective way to degrade the visual input, but rather to test whether the presence of a mask is a critical factor for the emergence of distractor interference under high levels of load. Thus, the critical outcome of this experiment is the fact that a significant distractor interference was found in both high load conditions, and this interference was statistically similar to the interference of the low load conditions. Thus, the exclusion of the mask did not eliminate or even reduce distractor interference with high levels of load. This issue is further explored in Experiment 4.

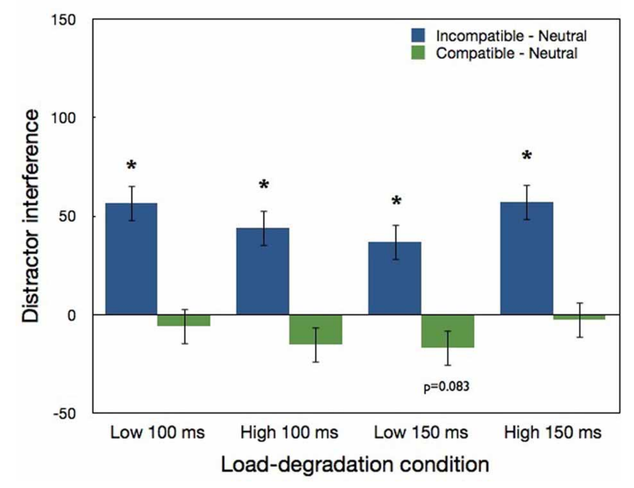

FIGURE 7 | Distractor interference (incompatible minus neutral) and distractor facilitation (compatible minus neutral) in Experiment 3 as a function load-degradation condition. "*" indicates a significant effect of the simple pairwise comparisons with neutral conditions. Error bars correspond to 1 SE.

EXPERIMENT 4

The results of Experiment 3 suggest that the discrepancy between our current Experiment 2 and Experiment 4 of our previous study (Marciano and Yeshurun, 2011) is not due to the presence of a backward mask because Experiment 3 did not include a mask, yet an interference was found in its high load condition. The only other methodological difference between the experiments is the fact that in Experiment 2 the variable of exposure duration was mixed. Hence, in Experiment 4 of Marciano and Yeshurun (2011) all the trials within a single block were similar apart from the compatibility of the distractor, while in Experiment 2 they also differed considerably in terms of the duration of the main letters display. The perceptual load theory, due to its passive view of attention, holds no place for effects that are related to such within-block variance. But a more active view of the attentional selectivity can accommodate effects that are due to within-block variability. This is because larger within-block variance creates more uncertainty regarding the demands of the upcoming trial, and this uncertainty may encourage the participants to adopt a different selection strategy than when there is less within-block variability. In this experiment we tested whether the emergence of distractor interference with high load levels was indeed an outcome of large within-block variability. To that end the variable of duration in this experiment was blocked. If the distractor interference in the high load condition found in Experiments 2, 3 is due to the fact that the variable of duration was mixed within a block, no such interference should be found here or at least its magnitude should decrease considerably.

MATERIALS AND METHODS

Participants

Eighteen students from the University of Haifa took part in this experiment for monetary reward or course credit. All had normal or corrected to normal vision and all were naive to the purpose of the study. None of them participated in the previous experiments.

Stimuli and procedure

The stimuli and procedure of this experiment were identical to Experiment 2 except for the fact that the variable of exposure duration was blocked. The experimental meeting included two consecutive sessions, each session included six blocks of trials, all with the same exposure duration—either 100 or 150 ms. The order of the duration sessions was counterbalanced across participants. Each block included 144 trials divided equally between the three compatibility conditions (compatible, incompatible, and neutral). Overall, each participant performed 1728 trials, 864 of each exposure duration condition and 576 of each load condition.

RESULTS AND DISCUSSION

As in previous experiments, we calculated IE scores for each condition of each participant, with the same RT exclusion criterion (excluding 0.36% from the total number of correct trials, after the exclusion of the first two blocks in each duration session that served as practice). These IE scores were submitted to a three-way repeated measures ANOVA, load (low vs. high) x exposure duration (150 vs. 100 ms) × compatibility (neutral, incompatible, or compatible). The means of RT, accuracy and IE scores for all the conditions are presented in **Table 4**. The main effect of load was significant [$F_{(1, 17)} = 100.95, p < 0.0001$]; performance was poorer (larger IE scores) with high than low load conditions. The main effect of compatibility was also significant [$F_{(2, 34)} = 59.87, p < 0.0001$]. Performance was best in the compatible condition and worst in the incompatible condition. The main effect of exposure duration was practically significant [$F_{(1, 17)} = 4.38, p = 0.0516$]; performance was better with the longer than shorter exposure duration. The two-way interaction between compatibility and exposure duration was also significant [$F_{(2, 34)} = 6.25, p < 0.005$]: distractor interference was significant in both exposure durations ($p < 0.0007$), yet it was larger with the 100 ms than 150 ms duration. Distractor facilitation was significant in 100 ms condition ($p < 0.02$) but not in the 150 ms condition.

The three-way interaction between load, exposure duration and compatibility was not significant. Nevertheless we performed LSD *post-hoc* analysis because of its theoretical importance. As can be seen in **Figure 8** and in **Table 4**, in the low load condition significant distractor interference was found in both 150 ms ($p < 0.03$) and 100 ms durations ($p < 0.0001$). However, similar to our previous experiments, but unlike Lavie and de Fockert (2003), the magnitude of this interference did not differ significantly between the two duration conditions. Also similar to our previous experiments, significant distractor interference in the high load condition emerged with both exposure durations ($p < 0.003$). Moreover, the magnitude of the distractor interference in the high load conditions of both durations did not differ significantly from the interference of the low load conditions. Regarding distractor facilitation, a significant difference ($p < 0.05$) was found for the low load 100 ms condition, and marginally significant difference ($p = 0.097$) was found for the high load 100 ms condition.

To sum, this experiment replicated the main findings of our previous experiments: degrading the quality of the visual input did not decrease the low load distractor interference, but also did not increase it. In addition, a significant distractor interference was found in the high load conditions, and this interference was statistically similar to the interference of the low load condition. Thus, blocking the duration variable did not eliminate or even reduce distractor interference with high levels of load.

GENERAL DISCUSSION

This study examined the effects of degrading the quality of the visual stimulus on distractor interference. To that end we degraded the stimuli in two different manners. In Experiment 1 we reduced the stimuli contrast and in Experiments 2–4 we

Table 4 | Mean correct RT, accuracy and IE scores (inverse efficiency = RT/accuracy) as a function of load-degradation and compatibility conditions in Experiment 4.

Load-degradation condition	*RT* (ms) Distractor compatibility				Accuracy (%) Distractor compatibility				*IE* scores Distractor compatibility			
	IC	*C*	*N*	Total	*IC*	*C*	*N*	Total	*IC*	*C*	*N*	Total
Low load 100	657	629	643	643	80.3	92.7	88.7	87.2	845	682	733	753
High load 100	679	675	690	681	64.4	76.5	75.1	72	1085	891	934	970
Low load 150	665	633	642	647	88.7	94.9	92.5	92	752	668	695	705
High load 150	693	697	689	693	73.1	80.9	79.6	77.9	962	872	880	905
Total	674	659	666		76.6	86.3	84		911	778	811	

IC, incompatible condition; C, compatible condition; N, neutral condition.

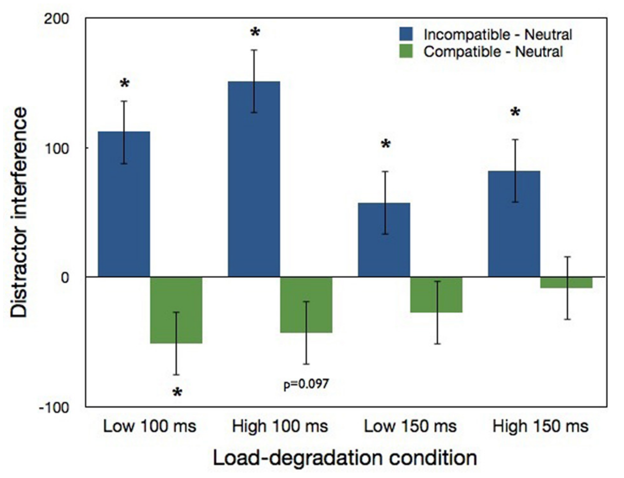

FIGURE 8 | Distractor interference (incompatible minus neutral) and distractor facilitation (compatible minus neutral) in Experiment 4 as a function load-degradation condition. "∗" indicates a significant effect of the simple pairwise comparisons with neutral conditions. Error bars correspond to 1 SE.

shortened exposure duration. The outcome was similar in all four experiments: degrading the quality of the visual input did not eliminate distractor interference. This finding is similar to Lavie and de Fockert (2003), however in that study only the target was degraded. This latter fact raises the possibility that distractor interference in Lavie and de Fockert's study "survived" degradation because in addition to mere degrading the quality of the target the degradation changed the conspicuity relationships between the target and distractor—making the distractor considerably more conspicuous than the target. Here, we degraded both relevant and non-relevant stimuli, and still found that distractor interference persists. However, Lavie and de Fockert also found that degrading the target under low levels of load increased the magnitude of distractor interference. They, therefore, concluded that while increasing perceptual load decreases distractor interference, increasing sensory load (i.e., degrading the sensory input) increases distractor interference. We found very little evidence in support of the conclusion that increasing sensory load increases interference. In almost all of the cases explored here (apart from a marginally significant effect in Experiment 2) there was no significant difference between the degraded and non-degraded conditions in terms of distractor interference. This discrepancy between our data and that of Lavie and de Fockert may be due to the conspicuity issue mentioned above. That is, in their study the degradation also made the target less conspicuous in comparison to the distractor and this resulted in increased interference from the more salient distractor. The issue of conspicuity will be further discussed below. Given the data accumulated thus far, it seems that the only solid conclusion one can make regarding stimulus degradation (or sensory load), is that it plays only a minor role, if at all, in determining the efficiency of the attentional selectivity.

Benoni and Tsal (2012) have recently reached a similar conclusion. They did not attempt to control for target distractor conspicuity relationships, as we did here. Hence, like Lavie and de Fockert (2003), their displays included only degradation of the target. Instead, they controlled for the effect of dilution. As these authors demonstrated in several studies (e.g., Benoni and Tsal, 2010; Tsal and Benoni, 2010), adding neutral letters to a low load display (i.e., diluting the distractor) eliminates distractor interference. This finding suggests that the typical lack of distractor interference in the high load condition may not be due to increase in demand for resources due to high levels of load, but to the fact that the display also includes neutral letters that dilute the distractor. In their recent study, Benoni and Tsal (2012) examined the effect of degrading the quality of the target when the effects of dilution are controlled for. Across their two experiments they compared the magnitude of distractor interference between displays of low-load-low-dilution (i.e., no neutral letters), low-load-high-dilution (i.e., with neutral letters and a cue marking target position), and high-load-high-dilution (i.e., with neutral letters but without the cue), each with and without target degradation (contrast and size reduction). They found that the main factor that determined the magnitude of distractor interference was not sensory load (or perceptual load), but rather the presence of neutral letters. Thus, Benoni and Tsal's findings are consistent with the assertion that sensory degradation has only a minor effect on the attentional selectivity.

The motivation stated in Lavie and de Fockert (2003) to examine sensory degradation was to rule out an alternative explanation claiming that the lack of distractor interference in the high load condition is due to the fact that the task in this condition was harder. That is, that the factor determining the attentional selectivity is not perceptual load but task difficulty. By showing that task difficulty in the degraded condition was high, but distractor interference was not reduced, Lavie and de Fockert (2003) could conclude that this alternative explanation is not valid. Our data also suggest that task difficulty *per se* is not a critical factor, because we often found large interference in the hard high load conditions. To examine more carefully the effect of task difficulty by itself, we plot in **Figure 9** distractor interference as a function of performance (IE scores) in the neutral condition for each of the participants in Experiments 2–4. We assume here that performance in the neutral condition is the most uncontaminated measure of task difficulty we have in this study. Also, we combined the last three experiments because of their high methodological similarity. As can be seen in **Figure 9**, there is only a weak relationship between the magnitude of distractor interference and performance in the neutral condition. Specifically, there is a marginally significant positive correlation ($r = 0.22$, $n = 60$, $p = 0.0923$): distractor interference is larger with worse performance[2]. Thus, this correlation is in the opposite direction to that suggested as an alternative explanation. In any case, this

[2]Similar analyses were performed on the RT and accuracy measures. With RTs there was no significant correlation ($r = -0.15$, $n = 60$, $p = 0.26$), even when one outlier participant was taken out of the analysis ($r = -0.13$, $n = 59$, $p = 0.34$). With accuracy there was also no significant correlation when all participants were included ($r = -0.2$, $n = 60$, $p = 0.12$), but when one outlier was taken out of the analysis this correlation reached statistical significance ($r = -0.33$, $n = 59$, $p < 0.02$). Note that the negative correlation in the case of accuracy is in the same direction as that found with IE scores—interference is larger with worse performance.

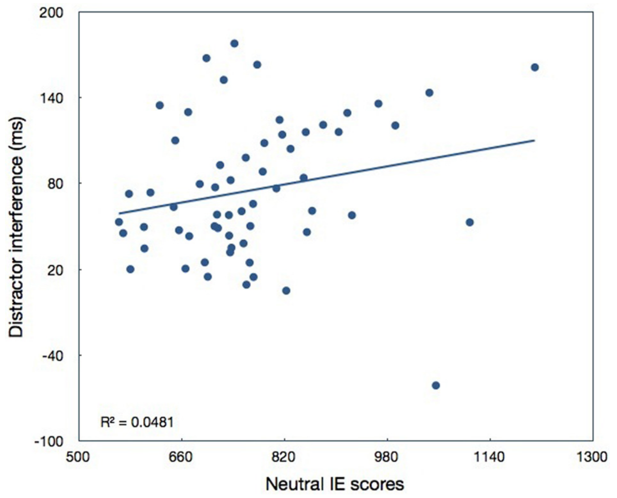

FIGURE 9 | Distractor interference as a function of performance in the neutral condition of Experiments 2–4.

correlation can only account for 4.8% of the variance in distractor interference. When one outlier is taken out of the analysis this correlation reaches statistical significance ($r = 0.364$, $n = 59$, $p < 0.005$). Still, even without the outlier, performance in the neutral condition (task difficulty) can only account for 13.3% of the variance in distractor interference. This leads to the conclusion that task difficulty *per se* does not play an important role in our ability to select relevant information, and the minor role it may have is in fact in the opposite direction to that assumed before, as larger interference was found with harder tasks.

Interestingly, perceptual load also did not emerge as a critical factor. In all of our experiments a reliable distractor interference was found in the high load condition. This interference was marginally significant in Experiment 1 and significant in Experiments 2–4. This high load interference was often of the same magnitude as the low load interference. Similar high load interference also emerged in Experiments 1–3 of our previous study (Marciano and Yeshurun, 2011). In that study we attributed the high load interference to uncertainty regarding the spatial location of the distractor, because when this uncertainty was reduced from 10 possible locations to two possible locations (Experiments 1–3 vs. Experiment 4 of that study), the high load interference was eliminated. However, in all of our current experiments there were only two possible distractor locations. Hence, the high load interference found here could not be attributed to high spatial uncertainty. These findings suggest, therefore, that although low level of uncertainty regarding the location of the distractor may be a necessary condition to allow efficient distractor exclusion, it is not a sufficient condition. Regardless of spatial uncertainty, the findings of the current study as well as our previous study suggest that the efficiency of the attentional selectivity does not depend on perceptual load, at least not in the way described by the perceptual load theory, because inefficient selectivity (i.e., distractor interference) is sometimes found only with low levels of load, but sometimes it is also found with high levels of load. That is, perceptual load is not a strong predictor of selection efficiency.

Indeed, the core tenets of the perceptual load theory were already challenged in the past [see Khetrapal (2010) for a review]. Several studies have demonstrated that efficient selection (i.e., the lack of distractor interference) is possible even under conditions of low perceptual load (e.g., Paquet and Craig, 1997; Johnson et al., 2002; Eltiti et al., 2005; Tsal and Benoni, 2010). More relevant to our current study are prior demonstrations of distractor interference under high load conditions (e.g., Chen, 2003; Theeuwes et al., 2004; Eltiti et al., 2005; Tsal and Benoni, 2010; Benoni and Tsal, 2012). Theeuwes et al. (2004), for instance, found that when high and low load conditions were intermixed within the same block, distractor interference was found in both conditions. They suggested that low perceptual load can bring about broad attentional processing that carries over to subsequent high load trials. This inter-trial influences account, however, cannot explain the high load interference found here because in all of the current experiments the load manipulation was blocked. Chen (2003) found that when the non-relevant and relevant information were part of the same object the levels of perceptual load did not modulate the degree of interference. This finding is also not applicable to the current study, because the relevant and non-relevant information in the current study always belonged to different objects. Eltiti et al. (2005) claim that the efficiency of selective attention depends not only on perceptual load but also on the saliency of the target and distractor in comparison to the neutral items. They found that increasing the target and distractor saliency by using a target that is slightly larger than the neutral letters and employing onset distractors, results in an interference effect even under high perceptual load. They suggested that because the target and the distractor were the most salient items both captured attention and this resulted in interference. However, because the target in our Experiments 2–4 was not more salient than the other letters, this saliency interpretation of the high load interference cannot account for our entire data set. Still, some of our findings in Experiment 1 may be due to saliency differences between target and distractor (see more below). Finally, as described above, diluting the effect of the distractor by adding to the display neutral letters that share features with the target and distractor, eliminates distractor interference (e.g., Tsal and Benoni, 2010; Benoni and Tsal, 2012). Most relevant to the current findings, these authors also found that when the low-load diluted condition is compared to the high-load condition larger distractor interference is observed in the high load than dilution condition. This is consistent with our findings of reliable high load interference, and further suggests that when the high load interference is compared to the interference in a diluted low load condition, rather than the typical not-diluted low load condition, the high load interference may be even larger than the low load interference.

Unlike the factors discussed above, the conspicuity of the target relative to the distractor does seem to play a role in determining the efficiency of the attentional selectivity. This is because distractor interference in Experiment 1 was significantly larger when the distractor was more conspicuous in comparison to the target (i.e., when only the target was degraded—LLTD) than when the target was more conspicuous in comparison to the distractor (i.e., when only the distractor was degraded—LLDD). This finding is consistent with Eltiti et al. (2005) claim that the saliency of the target is an important factor. They made the target more salient than the distractor by presenting the target as onset and the distractor as offset, and demonstrated that this eliminated distractor interference. In our Experiment 1 target relative saliency was manipulated via contrast reduction and the outcome was similar—considerably smaller interference with the less salient distractor. In the same line, reducing the saliency of the distractor by adding neutral items that share features with the distractor considerably reduces distractor interference (e.g., Benoni and Tsal, 2010, 2012; Tsal and Benoni, 2010). Nonetheless, the relative conspicuity of the target cannot be the only factor mediating attentional selectivity because the relative conspicuity of the target was identical in our current Experiments 2–4 and Experiment 4 of Marciano and Yeshurun (2011) as well as Experiment 1 of Lavie and Cox (1997), yet distractor interference was absent in the previous experiments (the latter two experiments) but present in the current experiments.

Given these different patterns of results obtained in highly similar experiments (in terms of their methodological details) there seems to be a need for reconsideration of theories of attentional selectivity suggested thus far. At this point we can only speculate that the diverse outcomes are due to complex interactions between multitude of factors that encourage the participants to adopt different strategies regarding distractor exclusion. For instance, maybe if the task is too easy the participants do not bother investing resources in inhibiting the distractor because a reasonable level of performance can be attained without such inhibition. But when the task is moderately hard, distractor inhibition is "worth" the investment because perceiving the distractor might have a more detrimental effect on performance. Still, if the task is particularly hard the participants may not have spare resources to invest in inhibition. Such non-monotonic effects of task difficulty could obscure the true function of this factor. In addition, if the target is more salient than the distractor, distractor inhibition may not be needed or fewer resources may be required to prevent interference. This may also alter the selection strategy adopted by the participants, independently from task difficulty. Above all, there might be factors that are related to individual differences (e.g., working memory capacity) that play a major role in determining the selection strategy adopted by the participants. Such factors may be the ones responsible for the different patterns of results obtained for similar experiments. Considerable additional research is required to shed light on this issue. Nevertheless, it is hard to see how the current and previous outcomes can fit into the passive view of the attentional selectivity offered by the perceptual load theory. It seems much more consistent with an active view of selectivity, in which distractor interference is prevented via an active inhibition of non-relevant stimuli (Marciano and Yeshurun, 2011). Such an active view of attentional selectivity is consistent with Torralbo and Beck's (2008) study, in which distractor interference was found only when the target and other non-relevant items were presented to different hemifields. That is, evidence of selectivity was found only when there were nearby non-relevant items that compete over neuronal representation. Such competitive interactions may encourage the participants to adopt a more strict selectivity strategy. Torralbo and Beck suggested that these active biasing processes operate to improve the representation of the target, but it is quite likely that both enhancement of the relevant information and inhibition of non-relevant information may take place simultaneously when a need to exclude the distractor arises.

To conclude, neither stimulus degradation, established via contrast reduction (Experiment 1) or brief exposure duration (Experiments 2–4), nor perceptual load affected distractor interference in a consistent way. Distractor interference could be found with or without stimulus degradation and under low or high levels of load. These findings suggest that both factors do not have a critical role in determining our ability to ignore non-relevant items. A more complex model of attentional selectivity is required to account for the diversity of results reported thus far.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: http://www.frontiersin.org/Cognition/10.3389/fpsyg.2013.00289/abstract

REFERENCES

Bahrami, B., Lavie, N., and Rees, G. (2007). Attentional load modulates responses of human primary visual cortex to invisible stimuli. *Curr. Biol.* 17, 509-513.

Benoni, H., and Tsal, Y. (2010). Where have we gone wrong? Perceptual load does not affect selective attention. *Vision Res.* 50, 1292–1298.

Benoni, H., and Tsal, Y. (2012). Controlling for dilution while manipulating load: perceptual and sensory limitations are just two aspects of task difficulty. *Psychon. Bull. Rev.* 19, 631–638.

Brand-D'Abrescia, M., and Lavie, N. (2007). Distractor effects during processing of words under load. *Psychon. Bull. Rev.* 14, 1153–1157.

Chen, Z. (2003). Attentional focus, processing load and Stroop interference. *Percept. Psychophys.* 65, 888–900.

Collignon, O., Girard, S., Gosselin, F., Roy, S., Saint-Amour, D., Lassonde, M., et al. (2008). Audio-visual integration of emotion expression. *Brain Res.* 1242, 126–135.

Eltiti, S., Wallace, D., and Fox, E. (2005). Selective target processing: perceptual load or distractor salience. *Percept. Psychophys.* 67, 876–885.

Eriksen, B. A., and Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a non search task. *Percept. Psychophys.* 16, 143–149.

Forster, S. and Lavie, N. (2007). High perceptual load makes everybody equal: eliminating individual differences in distractibility with load. *Psychol. Sci.* 18, 377–381.

Handy, T. C., Soltani, M., and Mangun, G. R. (2001). Perceptual load and visuocortical processing: event-related potentials reveal sensory-level selection. *Psychol. Sci.* 12, 213–218.

Johnson, D. N., McGrath, A., and McNeil, C. (2002). Cuing interacts with perceptual load in visual search. *Psychol. Sci.* 13, 284–287.

Khetrapal, N. (2010). Load theory of selective attention and the role of perceptual load: is it time for revision? *Eur. J. Cogn. Psychol.* 8, 1–8.

Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. *J. Exp. Psychol. Hum. Percept. Perform.* 21, 451–468.

Lavie, N., and Cox, S. (1997). On the efficiency of attentional selection: efficient visual search results in inefficient rejection of distraction. *Psychol. Sci.* 8, 395–398.

Lavie, N., and de Fockert, J. W. (2003). Contrasting effects of sensory limits and capacity limits in visual selective attention. *Percept. Psychophys.* 65, 202–212.

Lavie, N., and Robertson, I. (2001). The role of perceptual load in visual neglect: rejection of ipsilesional distractors is facilitated with higher central load. *J. Cogn. Neurosci.* 13, 867–876.

Mack, A., Pappas, Z., Silverman, M., and Gay, R. (2002). What we see: inattention and the capture of attention by meaning. *Conscious Cogn.* 21, 488–506.

Mack, A., and Rock, I. (1998). *Inattentional Blindness.* Cambridge, MA: MIT Press.

Marciano, H., and Yeshurun, Y. (2011). The effects of perceptual load in central and peripheral regions of the visual field. *Vis. Cogn.*19, 367–391.

Mayfrank, L., Kimmig, H., and Fischer, B. (1987). "The role of attention in the preparation of visually guided saccadic eye movements in man," in *Eye Movements: From Physiology to Cognition*, eds J. K. O'Regan and A. Levy-Schoen, (New York, NY: North-Holland), 37–45.

Maylor, E., and Lavie, N. (1998). The influence of perceptual load on age differences in selective attention. *Psychol. Aging* 13, 563–573.

Murphy, F. C., and Klein, R. M. (1998). The effects of nicotine on spatial and non-spatial expectancies in a covert orienting task. *Neuropsychologia* 36, 1103–1114.

Norman, D. A., and Bobrow, D. G. (1975). On data-limited and resource-limited processes. *Cognit. Psychol.* 7, 44–64.

Paquet, L., and Craig, G. L. (1997). Evidence for selective target processing with a low perceptual load flankers task. *Mem. Cognit.* 25, 182–189.

Roder, B., Kusmierek, A., Spence, C., and Schicke, T. (2007). Developmental vision determines the reference frame for the multisensory control of action. *Proc. Natl. Acad. Sci. U.S.A.* 104, 4753–4758.

Rorden, C., Guerrini, C., Swainson, R., Lazzeri, M., and Baylis, G. C. (2008). Event related potentials reveal that increasing perceptual load leads to increased responses for target stimuli and decreased responses for irrelevant stimuli. *Front. Hum. Neurosci.* 2:4. doi: 10.3389/neuro.09.004.2008

Spence, C., Kingstone, A., Shore, D. I. and Gazzaniga, M. S. (2001). Representation of visuotactile space in the split brain. *Psychol. Sci.* 12, 90–93.

Theeuwes, J. (1992). Perceptual selectivity for color and form. *Percept. Psychophys.* 51, 599–606.

Theeuwes, J., Kramer, A. F., and Belopolsky, A. V. (2004). Attentional set interacts with perceptual load in visual search. *Psychon. Bull. Rev.* 11, 697–702.

Torralbo, A., and Beck, D. M. (2008). Perceptual load-induced selection as a result of local competitive interactions in visual cortex. *Psychol. Sci.* 19, 1045–1050.

Townsend, J. T., and Ashby, F. G. (1983). *Stochastic Modelling of Elementary Psychological Processes.* New York, NY: Cambridge University Press.

Tsal, Y., and Benoni, H. (2010). Diluting the burden of load: perceptual load effects are simply dilution effects. *J. Exp. Psychol. Hum. Percept. Perform.* 36, 1645–1656.

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Low level perceptual, not attentional, processes modulate distractor interference in high perceptual load displays: evidence from neglect/extinction

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According to perceptual load theory (Lavie, 2005) distractor interference is determined by the availability of attentional resources. If target processing does not exhaust resources (with low perceptual load) distractor processing will take place resulting in interference with a primary task; however, when target processing uses-up attentional capacity (with high perceptual load) interference can be avoided. An alternative account (Tsal and Benoni, 2010a) suggests that perceptual load effects can be based on distractor dilution by the mere presence of additional neutral items in high-load displays so that the effect is not driven by the amount of attention resources required for target processing. Here we tested whether patients with unilateral neglect or extinction would show dilution effects from neutral items in their contralesional (neglected/extinguished) field, even though these items do not impose increased perceptual load on the target and at the same time attract reduced attentional resources compared to stimuli in the ipsilesional field. Thus, such items do not affect the amount of attention resources available for distractor processing. We found that contralesional neutral elements can eliminate distractor interference as strongly as centrally presented ones in neglect/extinction patients, despite contralesional items being less well attended. The data are consistent with an account in terms of perceptual dilution of distracters rather than available resources for distractor processing. We conclude that distractor dilution can underlie the elimination of distractor interference in visual displays.

Keywords: attention, perceptual load, dilution, neglect, extinction

INTRODUCTION

Everyday situations require a flexible and efficient selection mechanism that helps us deal with complex perceptual input, only a small portion of which is important for our current behavioral goal. Attentional selection is therefore required to facilitate the processing of targets and the inhibition (or filtering-out) of distractors. However, such selection mechanisms are not always optimal. Indeed, various scenarios may yield distractor processing that interferes with target responses (distractor interference).

Considerable research has been dedicated to describing the factors that influence such distractor interference (e.g., Eriksen and Eriksen, 1974; Lachter et al., 2004). In particular, perceptual load theory (Lavie and Tsal, 1994; Lavie, 1995) proposes that the capacity of attention resources is at the heart of distractor interference. That is, when target processing does not exhaust attentional capacity (when there is a low perceptual load), left-over resources will be allocated to the distractors, thereby producing interference. Conversely, when attentional resources are depleted (when there is a high perceptual load), distractor processing is reduced and consequently no distractor interference is observed. Thus, according to this account, the perceptual load present in a given task will determine the level of attention resources available and hence whether distractor interference occurs.

Studies looking into the effect of perceptual load on distractor interference have frequently contrasted conditions of low-load (where the target appeared by itself in one of several possible central positions) with conditions of high-load (where the target was embedded among several central neutral items; e.g., Bavelier et al., 2000; Lavie and Fox, 2000; Beck and Lavie, 2005). The efficacy of selection is measured by the effect of an incongruent relative to a neutral distractor appearing in the display. Typically, substantial interference is observed under low-load conditions, but this is either markedly reduced or completely eliminated under high-load conditions. According to perceptual load theory (e.g., Lavie, 1995), this reduced interference under the high-load condition is a direct consequence of depleted attentional resources which are required for processing the central display, leaving fewer spare resources to be captured by the irrelevant distractor. While the precise definition of perceptual load has been elusive a recent attempt (Torralbo and Beck, 2008) points to the amount of local competition for attention (potentially at a neuronal level) as the determinant of the perceptual load of the target and therefore the amount of resources that will be allocated for its processing (and consequently the remaining resources that will be allocated to distractor processing).

Recently, an alternative explanation has been proposed for the lack of distractor interference under conditions of high perceptual load. In a series of studies Tsal and Benoni (Benoni and Tsal, 2010, 2012; Tsal and Benoni, 2010a; Benoni et al., 2013) have proposed that low-level perceptual processes, rather than the availability of attentional resources, can explain reduced distractor interference. According to this account, the neutral items present in high-load displays (but not in low-load displays) compete together for perceptual representation. When distractors have similar features, their perceptual weight is jointly decreased (see Duncan and Humphreys, 1989) and as a consequence distractor representations are weakened and their effect on target identification diminishes (and distractor interference deceases). Critically, this alternative account holds that effects of perceptual dilution will occur even if the neutral elements are not attended, since their impact is at a pre-attentional, perceptual level of representation.

The dilution account has been supported in experiments using a variety of converging operations. For example, in one experiment Tsal and Benoni (2010a) presented the same multiple color display in a low-load (but high dilution) condition and in a high-load (and high dilution) condition (Tsal and Benoni, 2010a). However, in the former the target color was pre-known, thus allowing for a low-load processing mode, whereas in the latter it was not, hence necessitating an active search of the entire display. In another experiment, Tsal and Benoni (2010a) spatially separated the additional non-target items from the target item and thus introduced another condition in which perceptual load is low but dilution is high. Distractor interference was abolished under both conditions, giving support to the argument that the mere presence of non-target items rather than the perceptual load associated with target processing eliminates distractor interference. Similar evidence for the reduction of distractor interference with the addition of task-irrelevant elements – the dilution phenomenon – has been reported several other times in the literature (e.g., Kahneman and Chajczyk, 1983; Brown et al., 1995; Roberts and Besner, 2005). Note that, on this account, the manipulation of perceptual load where additional non-target items are introduced in the display for high-load conditions cannot distinguish between accounts highlighting the availability of attentional resources (perceptual load) or those highlighting low level perceptual processes (dilution) in determining distractor interference.

Recently, Lavie and Torralbo (2010) have argued that the dilution effect reported by Tsal and Benoni (2010a) is brought about by attentional factors that could still be incorporated within the perceptual load explanation. That is, it can be hypothesized that the non-target items presented in a dilution display attract attention in the same way that a distractor attracts attention in low-load displays. For instance, spatially separating the non-target items from the target will mean that only limited attentional resources are needed for target processing. The consequence of this may be that the remaining attentional resources can be allocated to both the distractor (as in the low-load displays) and the non-target items (as in the high-load displays). It follows that fewer resources are available for distractor processing compared with the low-load condition. This would result in reduced distractor interference. This proposal remains to be tested.

In order to contrast the two competing explanations of non-target items either attracting resources, or weakening perceptual representations of the distractor, we tested effects of dilution/load based on the addition of non-target items to a display, using patients with unilateral neglect/extinction. These patients are of interest because they are typically thought to allocate less attention to the contralesional side compared with the ipsilesional side of space (e.g., Heilman and Valenstein, 1979; Duncan et al., 1997). It should be noted that while somewhat different accounts have been proposed to explain unilateral neglect (e.g., a deficit in disengagement, Posner et al., 1984; hemispheric imbalance, Kinsbourne, 1987; to name two classical accounts) they do not challenge the premise that contralesional elements receive reduced attention resources (or none at all). It follows that the attentional resources allocated to non-target items should be weakened when they fall in the contralesional field of such patients. According to perceptual load theory, the ameliorating effect of extra non-target items separated from the target should be greater when those items fall outside (compared with inside) the contralesional field, since the items primarily consume attentional resources when they do not fall in the contralesional field. However when the items fall in the contralesional field they do not compete so strongly for attention leaving sufficient resources for other distractors to be processed and interference to occur. On the other hand, if additional items dilute the perceptual processing of other distractors, then the additional items may reduce distractor interference even when they fall on the contralesional side. We presented a target along with distractor stimuli (items that could be congruent or incongruent with the response to the target) in vertical arrays at the center of the screen (ensuring that the patients could respond to the stimuli). In the critical conditions we examined the effects of presenting neutral (non-response-related) stimuli in the contra- and ipsilesional fields of the patients. We assessed whether the lateralised non-target items disrupted distractor inference specifically when they appeared on the contralesional side – since this is the condition in which the perceptual load and dilution accounts make opposite predictions.

MATERIALS AND METHODS

PARTICIPANTS

Seven patients were tested. Four had unilateral damage centered on the inferior, posterior parietal cortex (three right, one left hemisphere). One patient had a silent lesion in her left occipital cortex in addition to right parietal damage (JB). One had suffered anoxia and had bilateral degeneration along with a lesion pronounced in the left posterior parietal cortex (MH). One had bilateral lesions to right frontal and left occipito-temporal cortex (AS). JB and the unilateral right parietal patients all presented with neglect and/or extinction on the left side; this was designated the contralesional side for these patients. The other patients presented with right-side neglect and/or extinction; this was designated the contralesional side for these individuals (see **Table 1** for clinical details of the patients). Prior to participating in the study the patients were clinically assessed for their neglect/extinction symptoms. The clinical

Table 1 | Demographic and clinical details for the patients.

Patients	Sex	Age	Lesion site	Clinical deficit	Etiology
JB	F	73	Right parietal and left occipital	Left allocentric neglect, left extinction	Stroke
MP	M	65	Right parietal-frontal-temporal	Left egocentric neglect and left extinction	Stroke
RH	M	74	Left temporo-parietal	Right allocentric neglect, right extinction	Stroke
MH	M	56	Left parietal plus bilateral degeneration	Right extinction	Anoxia
MC	M	62	Right temporo-parietal	Left egocentric neglect, left extinction	Stroke
AS	M	65	Right frontal and left occipito-temporal	Right extinction	Stroke
RP	M	52	Right temporo-parietal	Left egocentric neglect, left extinction	Stroke

The clinical measures here were based on the tests of spatial attention in the BCoS battery (Humphreys et al., 2012).

measure of neglect was based on the Apples cancelation task from the BCoS battery (Humphreys et al., 2012) which tests for both egocentric (missing targets across the page) and allocentric neglect (making false positive responses to distractors with a missing contralesional section, irrespective of their position on the page; see Bickerton et al., 2011). The clinical test of extinction, also from the BCoS, involved the patients detecting finger wiggles by the experimenter using unilateral or bilateral stimulus presentation conditions. A patient was classed as having extinction if they were worse at reporting a contralesional item under bilateral relative to unilateral conditions (age-matched controls do not show any such deficit under the standard clinical testing conditions; Humphreys et al., 2012).

In addition to this, the patients were given a lab test of neglect and extinction. In this case the patients were presented with unilateral or bilateral presentations of the letters A–D on a PC screen for 200 ms, with each letter appearing in either the left or right visual field. There were 24 unilateral left, 24 unilateral right, and 48 bilateral trials. A group of 20 normal participants, age-matched to the patients, made no more than one error when reporting the letters. The patients were classed as having extinction if they showed a drop in performance of 0.04 or more on bilateral relative to unilateral presentation trials (see Chechlacz et al., 2013). They were classified as showing some degree of neglect if they failed to report at least two items fewer on the contra- than the ipsilesional side under unilateral presentation conditions, and they passed the unilateral trials on the extinction test in the BCoS. All of the current patients either showed aspects of neglect or clinical extinction, relative to the age-matched control participants.

STIMULI AND APPARATUS

A PC with a 19 in VGA color monitor was used to display the stimuli. The experiment was created and run with E-Prime software. The viewing distance was approximately 60 cm so that each cm on the screen represented 1° of visual angle. The stimuli were presented in black (for the target, distractor, and neutral letters) or blue (for the fixation dots) on a white background. The target letter was either x or z, presented in lower case (Ariel, 20 pts; 0.4° by 0.5° of visual angle in width and height, respectively). The distractor letters were uppercase X or Z, which could be congruent or incongruent with the response to the target (Ariel, Bold typeface, 24 pts; 0.67° by 0.8° of visual angle in width and height, respectively). There were five possible non-target letters: k, s, m, v, and n which appeared in lowercase (Ariel, 20 pts; 0.4° by 0.5° of visual angle in width and height, respectively).

The target letter was presented in one of four possible positions in a vertical column along the vertical meridian centered on the center of the screen and positioned 0.5° of visual angle apart (from edge to edge). The distractor letter was presented in one of two positions, either 1° of visual angle above or below the vertical column. We presented both targets and distractors centrally to prevent the patients' lateralised attentional impairment affecting target or distractor processing. Instead of a single fixation point four blue dots presented in a central vertical column, 0.5 cm apart were used to direct the patients' eyes to the center of the screen. These dots served as place holders for the possible positions of the target (were centered on the possible target letter position; i.e., could appear 0.75°, 1.75° of visual angle above and below the center of the screen).

Three types of display were used. In the low-load display only the target and distractor letters were presented, with the target appearing in one of the four possible locations and with the distractor appearing above or below the possible target locations. Three black dots were also presented in the remaining three possible target locations (i.e., the four possible target locations were filled with one target letter and three black dots, **Figure 1**). In the high-load display the target and distractor letters were presented in the same way as in the low-load display, with the only difference being the inclusion of three neutral letters presented in the three empty target positions. (i.e., the display included four letters in the central column, one of which was the target and three of which were non-target letters with the distractor appearing above or below the four letter array). Finally in the dilution display the target and distractor appeared in the same way as in the low-load condition, however, now the three neutral letters appeared on a separate vertical column falling 1° of visual angle to the left or right of the central column, with the middle letter positioned on the horizontal meridian and the two other letters 0.5° of visual angle above and below the central letter. The neutral letters in the dilution condition were presented to either the contralesional or ipsilesional side of space, this counterbalanced the trials and discouraged any spatial strategies the patients may use.

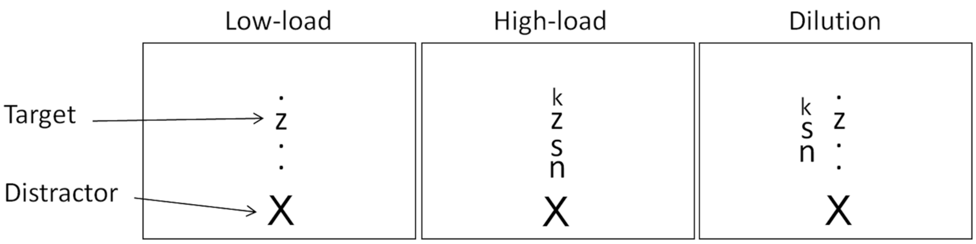

FIGURE 1 | Schematic view of the task. In all of the conditions patients were asked to verbally report whether a target letter x or z appeared in the centrally presented target array. In the low-load condition the target letter appeared alone in the central target array. In the high-load condition the target was intermixed with three non-target letters and in the dilution condition the target appeared alone in the target array with the three non-target letters appearing to the left or the right of the target array. All conditions included the presentation of distractor above or below the target array. Patients were instructed to ignore the identity of the distractor.

The identity of target, distractor and neutral letters were fully counterbalanced in each condition. Both the presentation of each of these letters, and the side on which the neutral letters appeared, were all equally frequent and randomly intermixed.

PROCEDURE

The experimenter initiated each trial after verifying that the patient was ready and focused on the screen. Each trial began with the presentation of the fixation array for 1500 ms which was followed by a 500 ms blank interval, followed by the presentation of the target stimuli for 500 ms. The patients were required to make a verbal response regarding the identity of the target letter (x or z) with the experimenter then immediately pressing the corresponding key on the keyboard ("L" for z and "K" for x). We used this procedure as some of the patients found it challenging to maintain a stimulus-response mapping between symbolic stimuli and specific motor responses. The experiment included three types of 32-trial blocks (low-load, high-load, and dilution). Within each block half of the trials were congruent (i.e., target and distractor were both x or were both z) and half were incongruent (i.e., target x and distractor Z, or target z and distractor X). Each block was run twice so that eventually 64 trials were collected for each condition. Blocks were presented in random order and separated by rest periods. As explained above we were primarily interested in the dilution condition when the non-target letters were presented to the contralesional side for the patient. Thus, the dilution blocks were further split into contralesional dilution and ipsilesional dilution conditions.

Prior to the beginning of the experimental run, three practice blocks of 16 trials each were given (one block per condition). During the practice blocks visual feedback on the screen was presented along with verbal feedback by the experimenter.

RESULTS

LABORATORY TEST OF NEGLECT/EXTINCTION

Table 2 presents the performance of the seven patients on the laboratory test of extinction. All but one patient (MH) showed neglect on this test, with poor report of a single target on the contralesional side of space (with errors ranging from 13 to 45%). In addition, all patients showed increased errors to contralesional targets when presented together with an ipsilesional target (range: 15–88% errors). These data verify that all patients exhibited neglect or extinction (and mostly both).

Table 2 | Data on the laboratory test of neglect/extinction.

Patients	Single	Double
JP	0.13	0.21
MP	0.42	0.88
RH	0.29	0.63
MH	0	0.15
MC	0.42	0.63
AS	0.45	0.38
RP	0.17	0.63

The table depicts the error rates exhibited by the patients when they had to identify an item presented to their contralesional side of space on its own (Single) or when the item co-occurred with another item presented to their ipsilesional side of space (Double). The report of ipsilesional items was in all cases at ceiling. A difference of 0.04 between the single and double item conditions indicates an extinction deficit that was outside of two SDs of the mean difference shown by a group of 20 age and education-matched control participants. The control participants also made no errors on single item trials. All the patients apart from MH showed a clinical deficit for single contralesional items, and all apart from AS showed a further drop in performance (extinction) for contralesional items on double item trials.

EFFECTS OF PERCEPTUAL LOAD/DILUTION

To incorporate both reaction times (RTs) and accuracy in a single measure and to avoid data contamination from a speed-accuracy trade off performance in the load/dilution task was assessed using an ANOVA on adjRT (RT/accuracy) with condition (low-load, high-load, contralesional dilution, and ipsilesional dilution) and congruency (congruent vs. incongruent) as within-subject factors. The adjRT data are depicted in **Figure 2**. A main effect of condition [$F(3,18) = 11.507$, $p = 0.001$, partial eta squared = 0.729] indicated that overall performance in the various load/dilution conditions differed.

Planned comparisons showed that adjRTs in the low-load (712 ms) condition were faster compared to the high-load condition [1372 ms; $t(6) = 5.735$, $p = 0.001$, Cohen $d = 1.735$] supporting the claim the two conditions differed in their perceptual load. Performance in the high-load condition (1372 ms) was

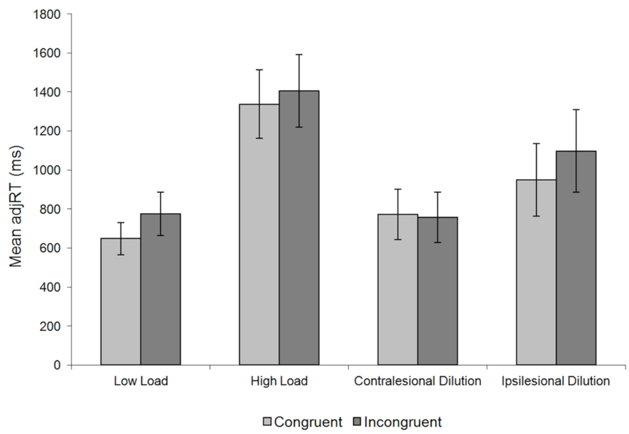

FIGURE 2 | Mean adjRT (±SEM) of patients' performance in the load/dilution task.

also significantly slower than in the contralesional dilution condition [765 ms; $t(6) = 9.398$, $p < 0.001$, Cohen $d = 1.47$] but there was no overall difference in RTs between the low-load and contralesional dilution conditions [$t(6) = 0.733$, $p = 0.491$, Cohen $d = 0.178$]. This pattern verifies that both the low-load and the contralesional dilution conditions had similar levels of perceptual load which increased for the high-load condition. In addition, presenting the non-target letters in the ipsilesional side of space for the patients (in the ipsilesional dilution condition) significantly slowed-down performance (1024 ms) compared with the low-load condition [$t(6) = 2.767$, $p = 0.033$, Cohen $d = 0.861$]. This pattern is consistent with ipsilesional distractors attracting attentional resources away from the centrally presented targets (e.g., Ladavas, 1987).

The ANOVA further resulted in a significant two-way interaction of condition and congruency [$F(3,18) = 4.239$, $p = 0.023$, partial eta squared = 0.486]. This interaction is most important here as our investigation focuses on the conditions which modulate distractor interference, manifested as a difference in performance between congruent or incongruent displays that is assessed using planned comparisons. As in previous perceptual load experiments we found that congruent (648 ms) and incongruent (775 ms) displays differed significantly under the low-load condition [$t(6) = 2.904$, $p = 0.027$, Cohen $d = 0.487$] but not under high-load condition [1338 vs. 1405 ms for congruent and incongruent, respectively; $t(6) = 1.405$, $p = 0.21$, Cohen $d = 0.14$]. Thus, the low-load display yielded significant distractor interference while the high-load condition did not. Critically, we also found no distractor interference in the contralesional dilution condition where patients performed similarly in congruent (773 ms) and incongruent (757 ms) displays [$t(6) = 0.71$, $p = 0.504$, Cohen $d = 0.047$]. Thus, distractor interference was eliminated by introducing contralesional neutral letters. Finally, we also found significant distractor interference in the ipsilesional dilution condition where performance was better for congruent displays (949 ms) than incongruent ones [1098 ms; $t(6) = 2.680$, $p = 0.044$, Cohen $d = 0.407$]. These results are inconsistent with the predictions of load theory (e.g., Lavie, 1995) but alternatively support the dilution account (e.g., Tsal and Benoni, 2010a) in showing that the mere presence of contralesional items led to the elimination of distractor interference, despite these items receiving reduced attention in the present patients. The results with extra-ipsilesional items are also inconsistent with load theory, since these items should attract attention and reduce resources to distractors (Lavie and Robertson, 2001).

DISCUSSION

The failure to filter out distractor stimuli (here manifested as distractor interference between congruent and incongruent trials) has been previously attributed to the availability of spare attentional capacity (Lavie, 2005). According to this account, when the perceptual load associated with processing the target is low (low-load conditions), unused attentional resources are allocated to distracters which in turn produces distractor interference. In contrast, when the perceptual load associated with processing the target is high (under high-load conditions) there are no attention resources left to process the distractor. Under these conditions, distractor interference is reduced. Recently, however, it has been suggested that distractor interference is modulated by low-level automatic perceptual processes that weaken its perceptual representation rather than the availability of attentional resources (Benoni and Tsal, 2010, 2012; Tsal and Benoni, 2010a,b). Specifically, multiple non-target elements lead to the dilution of perceptual processing for distractors, reducing their interference effects. We evaluated these accounts here by testing for effects of neutral (non-target) distractors in the contra- and ipsilesional fields of patients manifesting neglect and/or extinction on responses to central targets and distractors, based on the premise that contralesional distractors will receive less attention than stimuli presented at the center or in the ipsilesional field. We found several results of interest.

First, the patients were overall quicker in the low-load than the high-load condition. This verifies that perceptual load was manipulated successfully in these displays. Furthermore, overall adjRTs in the contralesional dilution condition (when neutral items appeared on the contralesional side) resembled those of the low-load condition, verifying that both conditions imposed only relatively low perceptual load and that few attentional resources were recruited by the contralesional distractors.

Second, distractor interference (the difference in performance between congruent and incongruent displays) was evident in the low-load but not in the high-load displays. This replicates prior studies on the effects of perceptual load (e.g., Bavelier et al., 2000; Lavie and Fox, 2000; Beck and Lavie, 2005). Critically, however, distractor interference was also eliminated in the contralesional dilution condition. Given that contralesional distractors should attract substantially reduced attentional resources here (evidenced both by the overall faster adjRTs to central targets in this condition and the patients' performance on the neglect/extinction lab test) this result is striking. The finding contradicts the idea that distractor interference is affected solely by the availability of spare attentional resources that could be allocated to distractor processing (Lavie, 1995). However, the result is consistent with perceptual dilution account (e.g., Benoni and Tsal, 2010, 2012; Tsal and Benoni, 2010a; Dittrich and Stahl, 2011; Marciano and Yeshurun, 2011; Wilson et al., 2011). According to this account, the perceptual processing of multiple items is diluted and, as this occurs at a pre-attentive level, the effect remains even when the items appear in the contralesional side of our patients.

As well as this result, we also found that distractor interference effects remained when the neutral letters appeared on the ipsilesional side. Again this result is difficult to reconcile with the standard account of perceptual load. Ipsilesional distractors should attract attention, given the biased allocation of spatial attention in our patients (see also Shalev and Humphreys, 2000). This should lead to resources being allocated to the target to reduce this competition leaving fewer resources to generate distractor interference (similar to the high-load condition). On the other hand, we would also expect the ipsilesional items to dilute perceptual processing, so a reduced effect of distractor interference is also predicted by the dilution account. However, it is possible that perceptual dilution still operated through the neutral items presented in the ipsilesional field, but this was overridden by attention to the ipsilesional stimuli. There is evidence that neglect and extinction to stimuli on the contralesional side can reflect enhanced attention to stimuli on the ipsilesional side (e.g., Ladavas, 1987; Shalev and Humphreys, 2000). Enhanced attention, even to items subject to perceptual dilution, may lead to resources being allocated to them and reducing attentional resources available for targets (in terms of load theory, this would be equivalent to the effects of an increased cognitive load). The result is that distractor interference then increases. Rather than the account of perceptual load, which assumes that competition between targets and distractors leads to exclusive allocation of resources to targets, this proposal holds that target-distractor competition weakens resource allocation to targets and increases interference.

In a previous study, Lavie and Robertson (2001) tested the performance of two neglect patients in a perceptual load task. A single distractor was presented on the ipsilesional side of space while perceptual load was manipulated by adding a single non-target item adjacent to a central target. The results of this study showed reduced distractor interference with the addition of a single non-target item. The data were used to suggest that in neglect patients, the addition of a single central item can lead to the enhanced focus of attention on the target (and reduced attentional resources being allocated to distractors). Note however, that the inclusion of the additional non-target item may also have diluted the perceptual strength of the distractor. Thus this result does not distinguish the load and dilution accounts. In the present study, however, we have contrasted the two alternative explanations directly by presenting letters to the contralesional side of space for the patients to prevent spontaneous allocation of attention toward them. This way, we were able to show that low-level perceptual processes and not the allocation of attentional resources, modulate distractor interference. If the allocation of attentional resources is critical to reducing distractor interference, as proposed by load theory, we should have still observed distractor interference effect here when non-target elements fall on the relatively unattended side of (contralesional) space. The data contradict this.

One may argue that the perceptual load account could be broadened to propose that unconsciously perceived stimuli also impose a perceptual load. Thus the contralesional non-target items presented here may increase the perceptual load associated with target processing. This argument may have merit if it was evident that the unconscious presence of the contralesional items imposed a high-perceptual load on target processing, so that target processing would then require more attention resource. The data does not support this idea however, as the contralesional condition here demonstrated low-load performance in our neglect/extinction patients based on absolute RTs.

The question still remains as to why distractor interference occurs at all and what are the dominant factors influencing efficient selection. Various authors have proposed factors other than load as major determinants of efficient selection (e.g., Paquet and Craig, 1997; Fournier et al., 2002; Johnson et al., 2002; Murray and Jones, 2002; Chen, 2003; Theeuwes et al., 2004; Eltiti et al., 2005; Chen and Chan, 2007; Cosman and Vecera, 2012). For example, Paquet and Craig (1997) found that efficient selection strongly depends on target-distractor similarity and that distractor interference could occur under low-load conditions for near but not far distractors. Chen (2003) showed that increasing perceptual load did not facilitate selection when both the distracting and the target stimuli were part of the same object. Theeuwes et al. (2004) argued that high-load and low-load conditions differ in attentional set. In high-load conditions participants engage in focused attention suitable for a serial search whereas in low-load conditions they employ a distributed mode which is suitable for identifying a single target that can occur in one of several positions. In support of their claim they showed that intermixing high-load and low-load displays abolished the load effect. Theeuwes et al. (2004) proposed that advance knowledge of perceptual load level rather than perceptual load *per se*, modulates the processing of irrelevant distractors.

In another study particularly relevant here, Eltiti et al. (2005) argued that the major factor contributing to effective selection is the relative salience of the target and the distractor rather than perceptual load. The idea that the salience of the distractor (rather than the perceptual load associated with the target) is of critical consequence in driving interference also fits with our results. Essentially, the dilution account suggests that the perceptual weight of the distractor is affected by the inclusion of non-target letters in the display. In other words, the presence of the non-target items reduces the perceptual saliency of the distractor which in turn results with reduced distractor interference.

A paper published in the present issue (Chen and Cave, 2013) further suggests that the dilution effect could be modulated by variables such as the spread of focused attention, the category of the stimulus, and preknowledge of the target. Future studies would need to further address the nature of the various factors influencing the processing of neutral items which in turn modulate the processing of distractors.

CONCLUSION

We have reported data showing that, in patients with visual neglect and extinction, contralesional, non-target letters reduced interference on centrally presented targets produced by central distractors. This occurred even though there was evidence that the contralesional items did not attract attentional resources (e.g., overall adjRTs did not differ from when only the central stimuli appeared). This finding contradicts an account of distractor interference in terms of perceptual load associated with the target but it does fit with the idea of perceptual dilution of the distractor from non-target items. On the other hand, with ipsilesional neutral items, distractor interference was maintained – again counter to load theory. We attribute this last result to ipsilesional stimuli capturing attention and removing resources from targets, over and above any effects of perceptual dilution.

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REFERENCES

Bavelier, D., Deruelle, C., and Proksch, J. (2000). Positive and negative compatibility effects. *Percept. Psychophys.* 62, 100–112. doi: 10.3758/BF03212064

Beck, D. M., and Lavie, N. (2005). Look here but ignore what you see: effects of distractors at fixation. *J. Exp. Psychol. Hum. Percept. Perform.* 31, 592–607. doi: 10.1037/0096-1523.31.3.592

Benoni, H., and Tsal, Y. (2010). Where have we gone wrong? Perceptual load does not affect selective attention. *Vision Res.* 50, 1292–1298. doi: 10.1016/j.visres.2010.04.018

Benoni, H., and Tsal, Y. (2012). Controlling for dilution while manipulating load: perceptual and sensory limitations are just two aspects of task difficulty. *Psychon. Bull. Rev.* 19, 631–638. doi: 10.3758/s13423-012-0244-8

Benoni, H., Zivoni, A., and Tsal, Y. (2013). Attentional sets influence perceptual load effects but not dilution effects. *Q. J. Exp. Psychol.* doi: 10.1080/17470218.2013.830629 [Epub ahead of print].

Bickerton, W. L., Samson, D., Williamson, J., and Humphreys, G. W. (2011). Separating forms of neglect using the apples test: validation and functional prediction in chronic and acute stroke. *Neuropsychology* 25, 567–580. doi: 10.1037/a0023501

Brown, T. L., Roos-Gilbert, L., and Carr, T. H. (1995). Automaticity and word perception: evidence from Stroop and Stroop dilution. *J. Exp. Psychol. Learn. Mem. Cogn.* 21, 1395–1411. doi: 10.1037/0278-7393.21.6.1395

Chechlacz, M., Rotshtein, P., Hansen, P. C., Deb, S., Riddoch, M. J., and Humphreys, G. W. (2013). The central role of the temporo-parietal junction and the superior longitudinal fasciculus in supporting multi-item competition: evidence from lesion-symptom mapping of extinction. *Cortex* 49, 487–506. doi: 10.1016/j.cortex.2011.11.008

Chen, Z. (2003). Attentional focus, processing load and Stroop interference. *Percept. Psychophys.* 65, 888–900. doi: 10.3758/BF03194822

Chen, Z., and Cave, K. R. (2013). Perceptual load vs. dilution: the roles of attentional focus, stimulus category, and target predictability. *Front.Psychol.* 4:327. doi: 10.3389/fpsyg.2013.00327

Chen, Z., and Chan, C. C. (2007). Distractor interference stays constant despite variation in working memory load. *Psychon. Bull. Rev.* 14, 306–312. doi: 10.3758/BF03194069

Cosman, J. D., and Vecera, S. P. (2012). Object-based attention overrides perceptual load to modulate visual distraction. *J. Exp. Psychol. Hum. Percept. Perform.* 38, 576–579. doi: 10.1037/a0027406

Dittrich, K., and Stahl, C. (2011). Nonconcurrently presented auditory tones reduce distraction. *Atten. Percept. Psychophys.* 3, 714–719. doi: 10.3758/s13414-010-0064-8

Duncan, L., and Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychol. Rev.* 96, 433–458. doi: 10.1037/0033-295X.96.3.433

Duncan, J., Humphreys, G. W., and Ward, R. (1997). Competitive brain activity in visual attention. *Curr. Opin. Neurobiol.* 7, 255–261. doi: 10.1016/S0959-4388(97)80014-1

Eltiti, S., Wallace, D., and Fox, E. (2005). Selective target processing: perceptual load or distractor salience? *Percept. Psychophys.* 67, 876–885. doi: 10.3758/BF03193540

Eriksen, B. A., and Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a non search task. *Percept. Psychophys.* 16, 143–149. doi: 10.3758/BF03203267

Fournier, L. R., Brown, K., and Winters, R. (2002). Identification of feature conjunctions does not increase the perceptual demands on attention. *J. Vis.* 2, 453. doi: 10.1167/2.7.453

Heilman, K. M., and Valenstein, E. (1979). Mechanisms underlying hemispatial neglect. *Ann. Neurol.* 5, 166–170. doi: 10.1002/ana.410050210

Humphreys, G. W., Bickerton, W.-L., Samson, D., and Riddoch, M. J. (2012). *BCoS: Individual Cognitive Profiling After Brain Injury*. London: Psychology Press.

Johnson, D. N., McGrath, A., and McNeil, C. (2002). Cuing interacts with perceptual load in visual search. *Psychol. Sci.* 13, 284–287. doi: 10.1111/1467-9280.00452

Kahneman, D., and Chajczyk, D. (1983). Tests of the automaticity of reading: dilution of Stroop effects by color-irrelevant stimuli. *J. Exp. Psychol. Hum. Percept. Perform.* 9, 497–509. doi: 10.1037/0096-1523.9.4.497

Kinsbourne, M. (1987). "Mechanisms of unilateral neglect," in *Neurophysiological and Neuropsychological Aspects of Spatial Neglect*, ed. M. Jeannerod (Amsterdam: North Holland), 69–86.

Lachter, J., Forster, K. I., and Ruthruff, E. (2004). Forty-five years after Broadbent (1958): still no identification without attention. *Psychol. Rev.* 111, 880–913. doi: 10.1037/0033-295X.111.4.880

Ladavas, E. (1987). Is the hemispatial deficit produced by right parietal lobe damage associated with retinal or gravitational coordinates. *Brain* 110, 167–180. doi: 10.1093/brain/110.1.167

Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. *J. Exp. Psychol. Hum. Percept. Perform.* 21, 451–468. doi: 10.1037/0096-1523.21.3.451

Lavie, N., (2005). Distracted and confused?: Selective attention under load. *Trends Cogn. Sci.* 9, 75–82. doi: 10.1016/j.tics.2004.12.004

Lavie, N., and Fox, E. (2000). The role of perceptual load in negative priming. *J. Exp. Psychol. Hum. Percept. Perform.* 26, 1038–1052. doi: 10.1037/0096-1523.26.3.1038

Lavie, N., and Robertson, I. H. (2001). The role of perceptual load in neglect: rejection of ipsilesional distractors is facilitated with higher central load. *J. Cogn. Neurosci.* 13 , 867–876. doi: 10.1162/089892901753165791

Lavie, N., and Torralbo, A. (2010). Dilution: a theoretical burden or just load? a reply to Tsal and Benoni (2010). *J. Exp. Psychol. Hum. Percept. Perform.* 36, 1657–1664. doi: 10.1037/a0020733

Lavie, N., and Tsal, Y. (1994). Perceptual load as a major determinant of the locus of selection in visual attention. *Percept. Psychophys.* 56, 183–197. doi: 10.3758/BF03213897

Marciano, H., and Yeshurun, Y. (2011). The effects of perceptual load in central and peripheral regions of the visual field. *Vis. Cogn.* 19, 367–391. doi: 10.1080/13506285.2010.537711

Murray, J. E., and Jones, C. (2002). Attention to local form information can prevent access to semantic information. *Q. J. Exp. Psychol. A Hum. Exp. Psychol.* 55, 609–625. doi: 10.1080/02724980143000370

Paquet, L., and Craig, G.L., (1997). Evidence for selective target processing with a low perceptual lead flankers task. *Mem. Cogni.* 25, 182–189.

Posner, M. I., Walker, J. A., Friedrich, F. J., and Rafal, R. D. (1984). Effects of parietal lobe injury on covert orienting of visual attention. *J. Neurosci.* 4, 1863–1874.

Roberts, M. A., and Besner, D. (2005). Stroop dilution revisited: evidence for domain-specific, limited-capacity processing. *J. Exp. Psychol. Hum. Percept. Perform.* 31, 3–13. doi: 10.1037/0096-1523.31.1.3

Shalev, L., and Humphreys, G. W. (2000). Biased attentional shifts associated with damage to the right parietal lobe. *Cogn. Neuropsychol.* 17, 339–365. doi: 10.1080/026432900380436

Theeuwes, J., Kramer, A. F., and Belopolsky, A. V. (2004). Attentional set interacts with perceptual load in visual search. *Psychon. Bull. Rev.* 11, 697–702. doi: 10.3758/BF03196622

Torralbo, A., and Beck, D. M. (2008). Perceptual-load-induced selection as a result of local competitive interactions in visual cortex. *Psychol. Sci.* 19, 1045–1050. doi: 10.1111/j.1467-9280.2008.02197.x

Tsal, Y., and Benoni, H. (2010a). Diluting the burden of load: perceptual load effects are simply dilution effects. *J. Exp. Psychol. Hum. Percept. Perform.* 36, 1645–1656. doi: 10.1037/a0018172

Tsal, Y., and Benoni, H. (2010b). Much dilution little load in Lavie and Torralbo's (2010) response: a reply. *J. Exp. Psychol. Hum. Percept. Perform.* 36, 1665–1668. doi: 10.1037/a0021907

Wilson, D. E., Muroi, M., and MacLeod, C. M. (2011). Dilution, not load, affects distractor processing. *J. Exp. Psychol. Hum. Percept. Perform.* 37, 319–335. doi: 10.1037/a0021433

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Conceptual and methodological concerns in the theory of perceptual load

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The present paper provides a short critical review of the theory of perceptual load. It closely examines the basic tenets and assumptions of the theory and identifies major conceptual and methodological problems that have been largely ignored in the literature. The discussion focuses on problems in the definition of the concept of perceptual load, on the circularity in the characterization and manipulation of perceptual load and the confusion between the concept of perceptual load and its operationalization. The paper also selectively reviews evidence supporting the theory as well as inconsistent evidence which proposed alternative dominant factors influencing the efficacy of attentional selection.

Keywords: perceptual load, dilution, early vs. late selection, selective attention, visual attention, distractor interference

Questions concerning the locus of selective attention have played a central role in the study of attention for decades, (see Johnston and Dark, 1986; Lachter et al., 2004, for reviews). According to early selection views (e.g., Broadbent, 1958; von Wright, 1968; Neisser, 1967; Treisman, 1969; Moran and Desimone, 1985), there is initial, involuntary, parallel processing of the physical characteristics of all stimuli. Based on the information derived from this initial analysis, a stimulus can be selected by attention for further processing to determine its meaning. Thus, unattended stimuli are not processed to the semantic level. On the other hand, late-selection accounts (e.g., Deutsch and Deutsch, 1963; Norman, 1968; Duncan, 1980; Tipper, 1985) hold that selection occurs later in the information processing stream such that there is also an initial, involuntary, parallel semantic processing of all stimuli. Hence, both the physical characteristics and the identities of unattended stimuli are processed.

Based on a distinction initially made by Kahneman and Treisman (1984), Lavie and Tsal (1994; Lavie, 1995) noted a fundamental difference between the two groups of studies described above. While early selection theories have relied on paradigms which were characterized in high display set size (e.g.,visual search paradigms) (for a review, see Pashler and Johnston, 1998), studies which supported the late selection views involved small display set sizes, usually no more than two different items, a target and a distractor (e.g., Eriksen and Eriksen, 1974; Keren et al., 1977; Gatti and Egeth, 1978; Kahneman and Henik, 1981; Hagenaar and van der Heijden, 1986; Miller, 1987; Paquet and Lortie, 1990). On the basis of this critical observation Lavie has developed her hybrid theory of selective attention. According to this theory, processing load of the relevant task determines the extent to which irrelevant distractors are processed. With a low load in relevant processing, leftover resources inevitably spillover to process irrelevant information. The processing of irrelevant distractors could be prevented only when the high load in relevant processing exhausts all attentional resources.

Various studies supported the predictions of perceptual load theory (e.g., Lavie and Cox, 1997; Rees et al., 1997, 2001; Maylor and Lavie, 1998; Lavie and Fox, 2000; Forster and Lavie, 2007, 2008) mostly using display set size for manipulating perceptual load. Thus, in the Low-Load Condition the target appeared by itself in one of several possible positions. In the High-Load Condition the target was embedded among several neutral letters. Distractor interference was measured by the effect of an incongruent relative to a neutral or congruent distractor appearing somewhat remotely from the target. Typically, substantial interference was observed under the Low-Load Condition, but was either markedly reduced or completely eliminated under the High-Load Condition. This finding was interpreted as supportive of load theory (e.g., Lavie, 1995) by assuming that reduced interference under the High-Load Condition is due to the fact that a great deal of attentional resources was required for searching the target among neutral items, leaving no spare resources to be captured by the irrelevant distractor.

Over the past two decades perceptual load theory has received a great deal of attention and has produced considerable impact in the attention literature. The present paper closely examines the basic tenets and assumptions of the theory as well as consistent and inconsistent evidence and identifies major conceptual and methodological flaws in the theory that have been largely ignored in the literature.

PERCEPTUAL LOAD THEORY IS AN EARLY, NOT A HYBRID, ACCOUNT OF SELECTIVE ATTENTION

The highly acclaimed contribution of perceptual load theory is its hybrid resolution of the early-late selection debate. That is, Perceptual load theory has been presented and recognized as a hybrid model in which the locus of attentional selection is flexible, either early or late, depending on the processing load of the relevant task. However, a closer look suggests that “perceptual load” has been erroneously treated as a hybrid account of attentional selection, since it is exclusively an early selection theory.

The early/late debate can be delineated by two main questions: (1) At which stage in the information processing stream attention selects information? (2). To what extent are unattended stimuli processed (or alternatively, which stages in the information processing stream necessitate attention)? According to perceptual load theory when prioritized relevant processing exhausts all of the available resources, irrelevant information remains unattended and is consequently excluded from processing. Thus, under high load conditions early selection occurs. Unlike the above, in low load presentations the relevant stimuli do not demand all of the available attentional resources, and spare resources unintentionally spill over to irrelevant stimuli, consequently enabling their processing. In other words, the theory actually proposes that the semantic processing of distractors in these displays occurs as a result of attentional allocation over their locations. This proposal is equivalent to the view that attention is necessary for semantic processing, and as such, it is strictly an early selection account. Moreover, since the theory states that the interference in low load conditions is produced by attentional allocation over irrelevant information, and not by preattentive semantic processing of the irrelevant information, the theory actually states that in principle, attention selects relevant information early in processing. Thus, the different patterns obtained under high load and low load presentations, according to the theory, are due to the efficiency of selection: while under high load conditions attentional selection is efficient, it is inefficient under low load conditions. Hence, the theory proposes a single early locus of selection irrespective of perceptual load, but a flexible answer regarding the efficiency of selection.

Why is load theory presented in the literature as a hybrid account concerning the question of the locus of selective attention? This oversight is probably the result of mistaking the efficiency of selection for the locus of selection. Another reason for this confusion could stem from the confusion between the questions of selective attention and selection of relevant from irrelevant information. The role of attention is indeed to select the relevant information, but if attention "spills over" to irrelevant information (as according to load theory, occurs in low load presentations), attentional selection is inefficient. Yet, the observer needs to select the relevant information in order to produce the correct response. Thus, the selection of relevant information from irrelevant will indeed occur late in processing stream, but it is important to realize that this late selection *is not* the *attentional* selection, but rather the decision that observers produce through higher cognitive functions.

In summary, load theory should not be presented as a theory which resolves the early/late debate by suggesting a hybrid model concerning this debate. Instead, load theory deserves its recognition for putting aside the archaic question of the locus of attentional selection, and by shifting the focus of interest to the more adaptive question: the question of the efficiency of selection.

ALTERNATIVES AND CONFOUNDS

Various studies reported inconsistencies with perceptual load theory and proposed that factors other than perceptual load are major determinants of efficient selectivity (e.g., Paquet and Craig, 1997; Fournier et al., 2002; Johnson et al., 2002; Murray and Jones, 2002; Chen, 2003; Theeuwes et al., 2004; Eltiti et al., 2005; Chen and Chan, 2007; Cosman and Vecera, 2012). Below are a few examples. Eltiti et al. (2005) argued that the major factor contributing to effective selection is the *relative salience* of the target and the distractor rather than perceptual load. They jointly manipulated perceptual load and onset (salient) or offset (not salient) of target and distractors. They found effective selection for onset target and offset distractor even under low load conditions, and distractor interference for offset target and onset distractor even under high load conditions. Eltiti et al. (2005) thus concluded that it is salience rather than load that determines the efficacy of selection. Evidence against load theory was also presented by Paquet and Craig (1997) who like Eltiti et al. (2005), showed efficient selectivity under low load conditions. They found that efficient selection heavily depends on *target-distractor similarity* and that distractor interference could occur under low load conditions for near but not far distractors, both for precued and uncued targets.

Chen (2003) showed that increasing perceptual load did not facilitate selection when both the distracting and the target stimuli were part of the same object (see also Kramer and Jacobson, 1991). Cosman and Vecera (2012) further demonstrated that during low-load search, filtering out of the flanker was enhanced when the to-be-ignored letter did not group with the search array (as in the high load search). Conversely, during high-load search, task-irrelevant flanker letters still exerted an interference effect if targets and flankers appeared in the same object (as in the low load search). They proposed that *object based attention effects* play a central role in selective attention regardless of the perceptual load of the task being performed.

Theeuwes et al. (2004) proposed another alternative. They argued that high load and low load conditions differ in *attentional set*. In the former the subjects are engaged in focused attention suitable for a serial search whereas in the latter they employ a distributed mode which is suitable for identifying a single target that can occur in one of several positions. In support of their claim they showed that intermixing high load and low load displays abolish the difference between the two. Consequently, Theeuwes et al. proposed that advance knowledge of perceptual load level rather than perceptual load *per se*, modulates the processing of irrelevant distractors.

Johnson et al. (2002) argue that *mode of attention (focused vs. distributed)* plays an important role in determining distractors interference. They demonstrated efficient selectivity in low load displays when precuing the position of the upcoming target as compared to a no-cue condition. They concluded that the cue in the low load condition helped participants to engage in selective and focused processing. A further interpretation for their findings will be discussed in the next section.

DILUTION vs. PERCEPTUAL LOAD

Tsal and Benoni (2010a,b; Benoni and Tsal, 2010) have argued that reduction of distractor interference under high load conditions, in set size manipulations, need not be attributed to increases in perceptual load resulting from the need to search for the target among the neutral letters. Instead, it could be due to the dilution of the distractor by the presence of neutral items characterizing high load presentations. These neutral items may play an important role in competing with the distractor for neuronal representation. Indeed, three different studies (Benoni and Tsal, 2010; Tsal and Benoni, 2010a; Wilson et al., 2011) distinguished between the possible effects of perceptual load and dilution by introducing low-load high-dilution displays. These displays contained neutral letters (as in high load conditions) capable of diluting the distractor. Yet, either stimulus or processing requirements allowed for a low load processing mode. For example, in a multiple color display the target color was preknown in the low load—high dilution condition but not in the high load condition (Tsal and Benoni, 2010a). In all experiments using a variety of converging operations distractor processing was either completely eliminated for these new displays (Benoni and Tsal, 2010; Tsal and Benoni, 2010a) or markedly reduced (Wilson et al., 2011) thereby supporting the conclusion that the elimination of distractor interference under the high load condition, repeatedly misattributed to perceptual load, is completely accounted for by dilution. The alternative dilution interpretation received further support from additional subsequent studies (e.g., Dittrich and Stahl, 2011; Marciano and Yeshurun, 2011; Benoni and Tsal, 2012; Benoni et al., in press; but see (Chen and Cave, 2013); Chen and Cave, for the role of attentional focus in dilution). The dilution manipulations produced two additional important findings. First, when the effect of dilution is properly controlled for, contrary to predictions of load theory, a reversed load effect emerges, i.e., it is high perceptual load, not low perceptual load, which produces greater distractor interference (Tsal and Benoni, 2010a; Wilson et al., 2011; Benoni and Tsal, 2012). A similar reversed load effect was reported by Chen and Cave (2013). Second, there is no need to postulate (e.g., Lavie and de Fockert, 2003) that different types of load produce opposite effects of distractor interference. Instead, when dilution is jointly manipulated with perceptual load, sensory degradation and cognitive load (Tsal and Benoni, 2011; Benoni and Tsal, 2012) the results clearly show that when dilution is properly controlled for any increase in task difficulty (be it perceptual, sensory or cognitive) increases distractor interference.

THE PROBLEM OF CIRCULARITY AND REFUTATION

What is perceptual load? Perceptual load is a vague term that has never been clearly and precisely defined and its consequent operationalizations have been guided primarily by intuitions rather than by a priori rigorous rules. How ought perceptual load be operationally defined? Tsal and Benoni (2010a) proposed that as a hypothetical construct perceptual load needs to be validated by related observables, either by its antecedents, i.e., related stimulus observables or by its consequents, i.e., related response observables. However, it seems that this concept could be verified by neither. Perceptual load could not be validated by rigorous stimulus manipulations since the manipulation of display size as well as the difficulty of perceptual operations are both confounded with sensory and cognitive factors, as will be detailed below. Nor could it be validated by its dependent measure. Overall reaction times (RT) (typically used as a manipulation check for perceptual load) assess overall task difficulty entailing sensory limitations and cognitive demands, and as such could not be used as a pure measure of perceptual load. Thus, the major building block of load theory, perceptual load, is a vague term that has never been clearly and precisely defined.

The lack of a coherent definition of the concept of perceptual load has resulted in circularity in the characterization of load, in the manipulation of load, and in reasoning. In the discussion bellow we will summarize the situations which illustrate this circularity and the consequent problem of refutation (Popper, 1959, 1963).

CIRCULARITY IN THE CHARACTERIZATION OF LOAD: IS THIS A HIGH-LOAD OR A LOW-LOAD CONDITION?

Although overall RT is the main measure that could be used to assess perceptual load, in some papers it was completely abandoned as a manipulation check and replaced by the presence or absence of distractor interference itself, which is supposed to be used as a dependent measure for confirming the predictions of perceptual load theory. For example, Lavie and Cox (1997) found that increasing display search size from one to four did not decrease distractor interference although it did increase the overall RT. Distractor interference was reduced only from set size six. Instead of concluding that these data are inconsistent with predictions of load theory, the authors concluded that "as long as the number of items in the relevant display does not exceed capacity, then irrelevant distractors are not rejected from processing" (p. 397). Similarly, Lavie and Robertson (2001), in assessing the effects of perceptual load on neglect, increased display size from two to three items. This manipulation did not increase overall RT but reduced distractor interference by almost 200 msec. Again, in the discussion, the authors considered the two conditions above as low load and high load respectively, although the manipulation check did not confirm any difference in perceptual load. Clearly, the absence of any a priori criteria for changes in perceptual load prevents the theory from standing the refutation criteria (Popper, 1959, 1963).

CIRCULARITY IN THE MANIPULATION OF LOAD: DEFINING LOAD ON THE BASIS OF STIMULUS RATHER THAN PROCESSING CONSIDERATIONS

In addition to the circularity associated with the definition of load, there also exists circularity with respect to how load is conceived and operationalized. Consider, for example, a study by Johnson et al. (2002). In this study the authors jointly manipulated display size and cuing. Following Lavie and Cox (1997), they presented a circular configuration containing one target (X or N) and five neutral letters that were flanked by a distractor. In the low load condition the neutral letters were all O's. In the high load condition the neutral letters were heterogeneous and shared features with the targets (and the distractors). Johnson et al. added a cuing manipulation and presented the displays either with no cue or with a 100% valid cue that always pointed to the expected target location. When the cue was absent distractor processing was evident in the low load condition but not in the high load condition, as predicted by perceptual load theory. However, with the valid cue there was no distractor processing even when perceptual load was low. The authors concluded that their results support a weak version of perceptual load theory in showing that while perceptual load is an important factor, it is not the only factor affecting attentional selection.

Table 1 presents a summary of the results obtained by Johnson et al. Most illuminating is condition 4. Given the presence of heterogeneous neutral letters it was inappropriately identified as a "high load" condition. However, the level of perceptual load should be dictated by processing considerations rather than by stimulus considerations. Hence, since the target is cued in advance, the heterogeneous display no longer constitutes a high load condition since the neutral letters need not be actively searched and could be easily filtered out (e.g., Yantis and Johnston, 1990). In further validation of this claim, one can see that the overall RT in this condition is indeed similar to that of the other two low-load conditions and substantially shorter than that of the high-load condition. In fact, this condition is similar to the dilution conditions (characterized by low load and high dilution) used in our previous studies (Benoni and Tsal, 2010, 2012; Tsal and Benoni, 2010a; Benoni et al., in press). Hence, the most important aspect of the results concerns the comparison between conditions 2 and 4 which shows that displays containing heterogeneous neutral letters with cuing (low load) and without cuing (high load), although substantially differing in overall RT (by 275 msec) equally reduced the congruency effect to 11 msec. Therefore, as argued by Tsal and Benoni (2010a); Benoni and Tsal (2010, 2012); Wilson et al. (2011), it is not perceptual load but rather the dilution resulting from the mere presence of neutral interfering letters that reduce or eliminate distractor processing.

The study of Johnson et al. (2002) illustrates the problem of refutation due to the absence of a coherent definition of the concept of perceptual load. Johnston and his colleagues established their important conclusion on the results obtained from condition 3 (i.e., Valid Cue—Low Load). Since they characterized condition 4 as High-Load (valid cue) condition they hypothesized a-priory a reduction in interference in this condition, although reduction of distractor interference in this condition should undermine the basic tenets of perceptual load theory.

CIRCULAR REASONING: FACE AND EMOTIONAL DISTRACTORS UNDER "PERCEPTUAL LOAD"

Several studies have manipulated load, not in order to test the predictions of load theory, but rather to test whether perception of faces (e.g., Lavie et al., 2003; Reddy and Wilken, 2004) or emotional stimuli (e.g., Bishop et al., 2007; Okon-Singer et al., 2007; Fox et al., 2012) requires attention. These studies have utilized typical load manipulations, but with faces or emotional stimuli used as distractors. The studies are based on the following rationale: If the specific distractor is processed automatically without attention then it is expected to produce interference, irrespective of the level of perceptual load in the task. If, on the other hand, distractor processing requires attention, then perceptual load is expected to reduce distractor interference.

Table 1 | Mean RTs (average of congruent, neutral and incongruent trials) and congruency effects (incongruent RT—congruent RT) for each condition in Johnson et al.'s (2002) study.

Condition	Mean RT	Congruency effect
1. No Cue—Low Load	584	65
2. No Cue—High Load	775	11
3. Valid Cue—Low Load	490	8
4. Valid Cue—High Load*	500	11

**This is, in fact, a Low Load condition characterized by low load and high dilution.*

The rationale underlying this line of studies is quite problematic as it produces circular reasoning. The basic assumption of these studies is that the distractors are attended in low load conditions and unattended in high load conditions. The problem is that this assumption cannot be stated a priori since it serves as the *hypothesis* and as the end product of the investigation of load theory, and since load theory uses the *same manipulations* of load, to *test* this assumption (see Lamy et al., 2013, for a related criticism). That is, for example, if manipulating load does not affect distractor interference it may indeed suggest that the processing of this distractor is not affected by attention, or is processed in a specific module. However, this same result can alternatively suggest that this finding is inconsistent with perceptual load theory thereby undermining its very basic assumptions. The latter possibility should not be taken lightly since various studies failed to replicate the traditional load effects (e.g., Theeuwes et al., 2004; Nelson et al., 2012, experiment 2; Tsal and Benoni, 2010a, experiments 2 and 4)., and also because the dilution account, discussed above, suggests that distractor interference does not necessarily depend on attentional resources. This suggestion is in agreement with several studies which find that the "flanker effect" is independent of spatial attentional resources (e.g., Cohen et al., 1995; Ro et al., 2002; Gronau et al., 2009). All these arguments strongly suggest that the notion of automaticity cannot be verified by manipulations of load.

VAGUENESS OF DEFINITIONS: CAN PERCEPTUAL, COGNITIVE, AND SENSORY LOADS BE TRULY DISTINGUISHED?

The expanded theory of load has argued that whereas increased perceptual load reduces irrelevant interference, increased cognitive load (Lavie et al., 2004) and increased sensory load (Lavie and de Fockert, 2003), in fact, produce the opposite effects. Hence, perceptual load needs to be precisely defined so that manipulations of perceptual load could a priori be clearly distinguished from those of cognitive or sensory load so as to rule out any possible bias in assigning a particular load to a particular pattern of results obtained. A close review of the literature suggests that this may be an impossible task because distinctions between these concepts are often fuzzy.

Lavie et al. (2004) defined cognitive load as a form of control which "depends on higher cognitive functions, such as working memory (WM), that are required for actively maintaining current processing priorities to ensure that low-priority stimuli do not gain control of behavior" (p. 339). The problem is that the most commonly used manipulation of perceptual load involves visual search, which cannot purely measure perceptual load because it entails a cognitive component. The operation of searching requires representing the target template, comparing the target template to possible candidate items, and categorizing the items in the search array. Indeed several models have proposed that visual WM is critical for a number of important operations during visual search, (e.g., Duncan and Humphreys, 1989; Bundesen, 1990). Consistent with this view, evidence from several neurophysiological studies have indicated that during visual search neurons that are selective for the search target often remain active during a delay period before the onset of the search display. Interestingly, the same brain areas show template-related activity during the delay period, followed by an enhanced response to a matching target during visual WM tasks (e.g., Miller and Desimone, 1993, 1994). Moreover, cells in inferior temporal (IT) cortex also show enhanced firing rates during search, just before a saccadic eye movement toward that target (Chelazzi et al., 1993). All of these findings led to the conclusion that visual search is just a variant of a WM task. This conclusion is most strongly supported by Luria and Vogel (2011) who tested directly the proposal that perceptual load manipulations by display set size, are actually WM manipulations. They follow the set-size manipulation conducted in Lavie and Cox (1997), and used an electrophysiological measure of WM capacity, the contralateral delay activity (CDA) amplitude, which is a marker for WM capacity (e.g., Vogel and Machizawa, 2004). Luria and Vogel found that the CDA amplitude was larger significantly in high load conditions compared to low load conditions, indicating a greater involvement of WM in the former. As far as the CDA amplitude does indeed reflect WM, then this finding provides direct evidence to the argument that perceptual load manipulations are confounded with memory load manipulations. The argument that perceptual load manipulations are confounded with those of cognitive load can be applied to other load manipulations not involving display size. For example, (Lavie, 1995) (Exp. 2) manipulated perceptual load by different processing requirements for identical displays. In the low load condition participants were required to identify a simple feature (e.g., to press a key only if the figure was red). In the high-load condition, they were required to perform a conjunction task (e.g., to react only if the figure was a red square). Obviously, the high perceptual load condition also imposed greater memory demands as it required two different sets of combinations of features to be held in memory. Moreover, Fournier et al. (2002) have demonstrated that Identification of feature conjunctions does not increase the perceptual demands on attention. Instead, slower responses associated with disjunction-conjunction judgments have been shown to be accounted for by differences in decision activation and/or memory demands (Fournier et al., 2004). Similar confounds of cognitive and perceptual demands are evident in other manipulations of perceptual load such as identifying the letter case vs. counting the number of syllables (Rees et al., 1997).

Manipulations of perceptual load and sensory degradation are also heavily confounded. For example, in the study of Lavie and de Fockert (2003, Exp.3), sensory load was manipulated by reducing visual acuity owing to position eccentricity of the target. This manipulation is confounded with perceptual load, since searching for a more peripheral target is perceptually more difficult irrespective of its reduced acuity. Empirical support for this claim is evident in this same Lavie and de Fockert study which showed a significant interaction between target position and perceptual load. Hence, the mechanisms mediating the effects of sensory and perceptual manipuolations are not independent. In a recent study, Fitousi and Wenger (2011) used more powerful measures as the hazard function of the response time distribution (Townsend and Ashby, 1978; Wenger and Gibson, 2004), along with signal detection theory, to test perceptual load theory. They found that contrary to the assumptions of load theory, perceptual load does, in fact, induce data limitations. Their findings provide strong evidence that perceptual load are confounded with sensory limitations.

The lack of clear distinctions between sensory degradation and perceptual load manipulations have produced confusing results in the literature. In an ERP study Handy and Mangun (2000) found that high perceptual load was associated with a decrease of the P1 and N1 components related to the distractor, supposedly in line with the prediction of load theory. The problem is that the same effects were obtained when perceptual load was manipulated by shortening target duration and superimposing a mask at its location, which are clearly sensory load manipulations. Similarly, in a recent fMRI study Yi et al. (2004) found that increasing the perceptual difficulty of a foveal target task attenuated processing of task-irrelevant background scenes. Again, the problem with this interpretation is that perceptual load was manipulated with sensory degradation, i.e., degrading the central face stimuli with random salt and pepper noise. It seems that the fuzziness of the concept of "perceptual load" permitted the assignment of the results to a particular load which fits the obtained pattern of results.

SUMMARY

The present paper closely examines the basic tenets and assumptions of the theory of perceptual load and identifies various conceptual and methodological flaws in the theory. The critical discussion focuses primarily on the definition of perceptual load, the difficulty in specifying the nature and level of load, the circularity in the characterization of load and the confusion between the concept of load and its operationalization. Unlike our previous studies (Benoni and Tsal, 2010, 2012; Tsal and Benoni, 2010a,b; Benoni et al., in press), the present paper is not restricted to set size manipulations but rather extends to a general discussion of load theory pertaining to all manipulations of perceptual load.

REFERENCES

Benoni, H., and Tsal, Y. (2010). Where have we gone wrong? Perceptual load does not affect selective attention. *Vision Res.* 50, 1292–1298. doi: 10.1016/j.visres.2010.04.018

Benoni, H., and Tsal, Y. (2012). Controlling for dilution while manipulating load: Perceptual and sensory limitations are just two aspects of task difficulty. *Psychon. Bull. Rev.* 19, 631–638. doi: 10.3758/s13423-012-0244-8

Benoni, H., Zivony, A., and Tsal, Y. (in press). Attentional sets influence perceptual load effects, but not dilution effects. *Q. J. Exp. Psychol.*

Bishop, S. J., Jenkins, R., and Lawrence, A. D. (2007). Neural processing of fearful faces: effects of anxiety are gated by perceptual capacity limitations. *Cereb. Cortex* 17, 1595–1603. doi: 10.1093/cercor/bhl070

Broadbent, D. E. (1958). *Perception and Communication*. London: Pergamon Press. doi: 10.1037/10037-000

Bundesen, C. (1990). A theory of visual attention. *Psychol. Rev.* 97, 523–547. doi: 10.1037/0033-295X.97.4.523

Chelazzi, L., Miller, E. K., Duncan, J., and Desimone, R. (1993). A neural basis for visual search in inferior temporal (IT) cortex. *Nature* 363, 345–347. doi: 10.1038/363345a0

Chen, Z. (2003). Attentional focus, processing load and Stroop interference. *Percept. Psychophys.* 65, 888–900. doi: 10.3758/BF03194822

Chen, Z., and Cave, K. R. (2013). Perceptual load vs. dilution: the roles of attentional focus, stimulus category, and target predictability. *Front. Cogn.* 4 *327*, 1–14.

Chen, Z., and Chan, C. C. (2007). Distractor interference stays constant despite variation in working memory load. *Psychon. Bull. Rev.* 14, 306–312. doi: 10.3758/BF03194069

Cohen, A., Ivry, R., Rafal, R. D., and Kohn, C. (1995). Activating response codes by stimuli in the neglected visual field. *Neuropsychology* 9, 165–173. doi: 10.1037/0894-4105.9.2.165

Cosman, J. D., and Vecera, S. P. (2012). Object-based attention overrides perceptual load to modulate visual distraction. *J. Exp. Psychol. Hum. Percept. Perform.* 38, 576–579. doi: 10.1037/a0027406

Deutsch, J. A., and Deutsch, D. (1963). Attention: some theoretical considerations. *Psychol. Rev.* 70, 80–90. doi: 10.1037/h0039515

Dittrich, K., and Stahl, C. (2011). Nonconcurrently presented auditory tones reduce distraction. *Atten. Percept. Psychophys.* 3, 714–719. doi: 10.3758/s13414-010-0064-8

Duncan, J. (1980). The locus of interference in the perception of simultaneous stimuli. *Psychol. Rev.* 87, 272–300. doi: 10.1037/0033-295X.87.3.272

Duncan, J., and Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychol. Rev.* 96, 433–458. doi: 10.1037/0033-295X.96.3.433

Eltiti, S., Wallace, D., and Fox, E. (2005). Selective target processing: perceptual load or distractor salience. *Percept. psychophys.* 67, 876–885.

Eriksen, C. W. (1995). The flanker task and response competition: a useful tool for investigating a variety of cognitive problems. *Vis. Cogn.* 2, 101–118. doi: 10.1080/13506289508401726

Eriksen, B. A., and Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a non search task. *Percept. Psychophys.* 16, 143–149. doi: 10.3758/BF03203267

Fitousi, D., and Wenger, M. J. (2011). Processing capacity under perceptual and cognitive load: a closer look at load theory. *J. Exp. Psychol. Hum. Percept. Perform.* 37, 781–798. doi: 10.1037/a0020675

Forster, S., and Lavie, N. (2007). Attentional capture by entirely irrelevant distractors. *Vis. Cogn.* 16, 200–214. doi: 10.1080/13506280701465049

Forster, S., and Lavie, N. (2008). Failures to ignore entirely irrelevant distractors: the role of load. *J. Exp. Psychol. Appl.* 14, 73–83.

Fournier, L. R., Brown, K., and Winters, R. (2002). Identification of feature conjunctions does not increase the perceptual demands on attention. *J. Vis.* 2, 453.

Fournier, L. R., Herbert, R. J., and Farris, C. (2004). Demands on attention and the role of response priming in visual discrimination of feature conjunctions. *J. Exp. Psychol. Hum. Percept. Perform.* 5, 836–852. doi: 10.1037/0096-1523.30.5.836

Fox, E., Yates, A., and Ashwin, C. (2012). Trait anxiety and perceptual load as determinants of emotion processing in a fear conditioning paradigm. *Emotion* 12, 236–249. doi: 10.1037/a0025321

Gatti, S. V., and Egeth, H. E. (1978). Failure of spatial selectivity in vision. *Bull. Psychon. Soc.* 11, 181–184.

Gronau, N., Cohen, A., and Ben-shakhar, G. (2009). Distractor interference in focused attention tasks is not mediated by attention capture. *Q. J. Exp. Psychol.* 62, 37–41.

Hagenaar, R., and van der Heijden, A. H. C. (1986). Target-noise separation in visual selective attention. *Acta Psychol.* 62, 161–176. doi: 10.1016/0001-6918(86)90066-1

Handy, T. C., and Mangun, G. R. (2000). Attention and spatial selection: Electrophysiological evidence for modulation by perceptual load. *Percept. Psychophys.* 62, 175–186. doi: 10.3758/BF03212070

Johnson, D. N., McGrath, A., and McNeil, C. (2002). Cuing interacts with perceptual load in visual search. *Psychol. Sci.* 13, 284–287. doi: 10.1111/1467-9280.00452

Johnston, W. A., and Dark, V. J. (1986). Selective attention. *Annu. Rev. Psychol.* 37, 43–75. doi: 10.1146/annurev.ps.37.020186.000355

Kahneman, D., and Henik, A. (1981). "Perceptual organization and attention," in *Perceptual Organization,* eds M. Kubovy and J. R. Pomerantz (Hillsdale, NJ: Erlbaum), 181–211.

Kahneman, D., and Treisman, A. (1984). "Changing views of attention and automaticity," in *Varieties of Attention,* eds R. Parasuraman and D. R. Davies (New York, NY: Academic Press), 29–61.

Keren, G., O'Hara, W. P., and Skelton, J. M. (1977). Levels of noise processing and attentional control. *J. Exp. Psychol. Hum. Percep. Perform.* 3, 653-664. doi: 10.1037/0096-1523.3.4.653

Kramer, A. F., and Jacobson, A. (1991). Perceptual organization and focused attention: the role of objects and proximity in visual processing. *Percept. Psychophys.* 50, 267–284. doi: 10.3758/BF03206750

Lachter, J., Forster, K. I., and Ruthruff, E. (2004). Forty-five years after Broadbent (1958): still no identification without attention. *Psychol. Rev.* 111, 880–913. doi: 10.1037/0033-295X.111.4.880

Lamy, D., Leber, A. B., and Egeth, H. E. (2013). "Selective attention," in *Handbook of Psychology, Experimental Psychology, 2nd Edn*, Vol. 4 eds R. W. Proctor and I. B.Weiner (Hoboken, NJ: John Wiley and Sons Inc), 267–294.

Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. *J. Exp. Psychol. Hum. Percept. Perform.* 21, 451–468. doi: 10.1037/0096-1523.21.3.451

Lavie, N., and Cox, S. (1997). On the efficiency of visual selective attention: efficient visual search leads to inefficient distractor rejection. *Psychol. Sci.* 8, 395–398. doi: 10.1111/j.1467-9280.1997.tb00432.x

Lavie, N., and de Fockert, J. W. (2003). Contrasting effects of stimulus degradation and resource limitation in visual selective attention. *Percept. Psychophys.* 65, 202–212.

Lavie, N., and Fox, E. (2000). The role of perceptual load in negative priming. *J. Exp. Psychol. Hum. Percep. Perform.* 26, 1038–1052. doi: 10.1037/0096-1523.26.3.1038

Lavie, N., Ro, T., and Russell, C. (2003). The role of perceptual load in processing distractor faces. *Psychol. Sci.* 14, 510–515. doi: 10.1111/1467-9280.03453

Lavie, N., and Robertson, I. H. (2001). The role of perceptual load in neglect: rejection of ipsilesional distractors is facilitated with higher central load. *J. Cogn. Neurosci.* 13, 867–876. doi: 10.1162/089892901753165791

Lavie, N., Hirst, A., de Fockert, J. W., and Viding, E. (2004). Load theory of selective attention and cognitive control. *J. Exp. Psychol. Gen.* 133, 339–354. doi: 10.1037/0096-3445.133.3.339

Lavie, N., and Tsal, Y. (1994). Perceptual load as a major determinant of the locus of selection in visual attention. *Percept. Psychophys.* 56, 183–197. doi: 10.3758/BF03213897

Luria, R., and Vogel, E. K. (2011). Visual search demands dictate reliance on working memory storage. *J. Neurosci.* 20, 6199–6207. doi: 10.1523/JNEUROSCI.6453-10.2011

Marciano, H., and Yeshurun, Y. (2011). The effects of perceptual load in central and peripheral regions of the visual field. *Vis. Cogn.* 19, 367–391. doi: 10.1080/13506285.2010.537711

Maylor, E. A., and Lavie, N. (1998). The influence of perceptual load on age differences in selective attention. *Psychol. Aging* 13, 563–573. doi: 10.1037/0882-7974.13.4.563

Miller, J. (1987). Priming is not necessary for selective attention failures: semantic effects of unattended, unprimed letters. *Percept. Psychophys.* 41, 419–434. doi: 10.3758/BF03203035

Miller, E. K., and Desimone, R. (1993). Scopolamine affects short-term memory but not inferior temporal neurons. *Neuroreport* 4, 81–84. doi: 10.1097/00001756-199301000-00021

Miller, E. K., and Desimone, R. (1994). Parallel neuronal mechanisms for short term memory. *Science* 263, 520–522. doi: 10.1126/science.8290960

Moran, J., and Desimone, R. (1985). Selective attention gates visual processing in the extrastriate cortex. *Science* 229, 782–784. doi: 10.1126/science.4023713

Murray, J. E., and Jones, C. (2002). Attention to local form information can prevent access to semantic information. *Q. J. Exp.Psychol. A* 55, 609–625.

Neisser, U. (1967). *Cognitive Psychology*. New-York: Appleton-Century-Crofts.

Nelson, M. D., Crisostomo, M., Khericha, A., Russo, F., and Thorne, G. L. (2012). Classic debates in selective attention: early vs. late, perceptual load vs. dilution, mean RT vs. measures of capacity. *Perception* 41, 997. doi: 10.1068/p7309

Norman, D. A. (1968). Toward a theory of memory and attention. *Psychol. Rev.* 75, 522–536. doi: 10.1037/h0026699

Okon-Singer, H., Tzelgov, J., and Henik, A. (2007). Distinguishing between automaticity and attention in the processing of emotionally significant stimuli. *Emotion* 7, 147–157. doi: 10.1037/1528-3542.7.1.147

Paquet, L., and Craig, G. L. (1997). Evidence for selective target processing with a low perceptual load flankers task. *Mem. Cognit.* 25, 182–189. doi: 10.3758/BF03201111

Paquet, L., and Lortie, C. (1990). Evidence for early selection: precuing target location reduces interference from same-category distractors. *Percept. Psychophys.* 48, 382–388. doi: 10.3758/BF03206692

Pashler, H., and Johnston, J. C. (1998). "Attentional limitations in dual-task performance," in *Attention,* eds H. Pashler (Hove, England: Psychology Press), 155–189.

Popper, K. R. (1959). *The Logic of Scientific Discovery*. London, England: Hutchinson and Co.

Popper, K. (1963). "Science: conjectures and refutations," in *Conjectures and Refutations*, (London, Routledge: Kegan Paul), 33–55.

Reddy, L., and Wilken, P. (2004). Face-gender discrimination is possible in the near—absence of attention. *J. Vis.* 4, 106–117.

Rees, G., Frith, C. D., and Lavie, N. (1997). Modulating irrelevant motion perception by varying attentional load in an unrelated task. *Science* 278, 1616–1619. doi: 10.1126/science.278.5343.1616

Rees, G., Frith, C., and Lavie, N. (2001). Processing of irrelevant visual motion during performance of an auditory attention task. *Neuropsychologia* 39, 937–949. doi: 10.1016/S0028-3932(01)00016-1

Ro, T., Machado, L., Kanwisher, N., and Rafal, R. (2002). Covert orienting to the locations of targets and distractors: effects on response channel activation in a flanker task. *Q. J. Exp. Psychol. A* 55, 917–936.

Theeuwes, J., Kramer, A. F., and Belopolsky, A. V. (2004). Attentional set interacts with perceptual load in visual search. *Psychon. Bull. Rev.*11, 697–702. doi: 10.3758/BF03196622

Tipper, S. P. (1985). The negative priming effect: inhibitory priming by ignored objects. *Q. J. Exp. Psychol. A* 37, 571–590.

Townsend, J. T., and Ashby, F. G. (1978). "Methods of modeling capacity in simple processing systems," in *Cognitive Theory,* Vol. 3, eds J. Castellan and F. Restle (Hillsdale, NJ: Erlbaum), 200–239.

Treisman, A. M. (1969). Strategies and models of selective attention. *Psychol. Rev.* 76, 282–299. doi: 10.1037/h0027242

Tsal, Y., and Benoni, H. (2010a). Diluting the burden of load: perceptual load effects are simply dilution effects. *J. Exp. Psychol. Hum. Percept. Perform.* 36, 1645–1656.

Tsal, Y., and Benoni, H. (2010b). Much dilution little load in Lavie, and Torralbo's, (2010) response: a reply. *J. Exp. Psychol. Hum. Percept. Perform.* 36, 1665–1668.

Tsal, Y., and Benoni, H. (2011). *Dilution and Task Difficulty*, *But not Load*, *Affects Selective Attention.* Paper presented at the VSS Annual meeting, Naples Florida.

Vogel, E. K., and Machizawa, M. G. (2004). Neural activity predicts individual differences in visual working memory capacity. *Nature* 428, 748–751. doi: 10.1038/nature02447

von Wright, J. M. (1968). Selection in visual immediate memory. *Q. J. Exp. Psychol.* 20, 62–68.

Wenger, M. J., and Gibson, B. S. (2004). Using hazard functions to assess changes in processing capacity in an attentional cuing paradigm. *J. Exp. Psychol. Hum. Percept. Perform.* 30, 708–719. doi: 10.1037/0096-1523.30.4.708

Wilson, D. E., Muroi, M., and MacLeod, C. M. (2011). Dilution, not load, affects distractor processing. *J. Exp. Psychol. Hum. Percept. Perform.* 37, 319–335. doi: 10.1037/a0021433

Yantis, S., and Johnston, J. C. (1990). On the locus of visual selection: evidence from focused attention tasks. *J. Exp. Psychol. Hum. Percept. Perform.* 16, 135–149. doi: 10.1037/0096-1523.16.1.135

Yi, D. J., Woodman, G. F., Widders, D., Marois, R., and Chun, M. M. (2004). Neural fate of ignored stimuli: Dissociable effects of perceptual and working memory load. *Nat. Neurosci.* 7, 992–996. doi: 10.1038/nn1294

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Perceptual load vs. dilution: the roles of attentional focus, stimulus category, and target predictability

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Many studies have shown that increasing the number of neutral stimuli in a display decreases distractor interference. This result has been interpreted within two different frameworks; a perceptual load account, based on a reduction in spare resources, and a dilution account, based on a degradation in distractor representation and/or an increase in crosstalk between the distractor and the neutral stimuli that contain visually similar features. In four experiments, we systematically manipulated the extent of attentional focus, stimulus category, and preknowledge of the target to examine how these factors would interact with the display set size to influence the degree of distractor processing. Display set size did not affect the degree of distractor processing in all situations. Increasing the number of neutral items decreased distractor processing only when a task induced a broad attentional focus that included the neutral stimuli, when the neutral stimuli were in the same category as the target and distractor, and when the preknowledge of the target was insufficient to guide attention to the target efficiently. These results suggest that the effect of neutral stimuli on the degree of distractor processing is more complex than previously assumed. They provide new insight into the competitive interactions between bottom-up and top-down processes that govern the efficiency of visual selective attention.

Keywords: selective attention, distractor interference, perceptual load, dilution, attentional focus

INTRODUCTION

When a target is presented with distractors in a search array, the distractors are often processed to some extent along with the target, resulting in increased response latencies when the target and distractors indicate different responses compared with when they indicate the same response (e.g., Eriksen and Hoffman, 1973; Eriksen and Eriksen, 1974; Miller, 1987). This response congruency effect has been observed in a variety of paradigms (e.g., Eriksen and St. James, 1986; Kramer and Jacobson, 1991; Chen and Cave, 2006). Even when a search array appears to facilitate target selection via optimal attentional focusing, evidence of distractor processing has still been found (e.g., Gatti and Egeth, 1978; Miller, 1991), showing that attentional selection is often inefficient. Understanding the mechanisms that modulate the degree of distractor processing is important, because it helps to shed light on the locus of attentional selection and how bottom-up and top-down processes interact in visual information processing. This study focuses on the factors that affect distractor processing in visual search.

Although the response congruency effect is frequently observed in selective attention tasks, it does not always appear. Lavie and Tsal (1994) and Lavie (1995) noted that the magnitude of the effect, which indicates the degree of distractor processing, is closely linked to the perceptual load required of a task, with a larger effect associated with a low perceptual load task and a smaller effect with a high perceptual load task. For example, in one experiment (Lavie, 1995, Experiment 1), Lavie varied the target-distractor response congruency (congruent, neutral, and incongruent) and the perceptual load involved in selecting the target (low vs. high). Perceptual load was manipulated via adjusting the number of elements in the display. In the low load condition, the target was shown with a single distractor. In the high load condition, it was shown with several neutral stimuli in addition to the distractor. A larger response congruency effect was found in the low compared with the high perceptual load condition. Based on this and other similar results, [Lavie (1995); see also Lavie and Tsal (1994)] proposed a perceptual load theory, in which perception is an automatic process with a limited pool of resources. To the extent there is spare capacity beyond what is used in processing the target, perception proceeds involuntarily until all the resources are used up. When a task involves a low perceptual load, distractor processing occurs because of the spillover resources. When a task involves a high perceptual load, distractor processing is either reduced or eliminated due to the unavailability of spare resources. Thus, the degree of distractor processing depends on the amount of leftover resources, which, in turn, is determined by the perceptual load of a task. Since its proposal, evidence in support of the perceptual load theory has been reported in many studies (see Lavie, 2005, for a review).

However, despite this supporting evidence, there is also a growing number of studies that have shown results inconsistent with the perceptual load theory. Whereas the typical perceptual load effect, i.e., a large response congruency effect with low perceptual load, was observed when the low and high perceptual load trials were presented in separate blocks (e.g., Lavie, 1995; Lavie and Cox, 1997; Lavie and Fox, 2000), the effect was reduced or even eliminated when the two types of trials were intermixed within the same block (Murray and Jones, 2002; Theeuwes et al., 2004). The perceptual load effect was also eliminated, and sometimes even reversed, when the location of the target was precued (Paquet and Craig, 1997; Johnson et al., 2002), when the target and distractor were placed in separate objects or perceptual groups (Baylis and Driver, 1992; Tsal and Benoni, 2010; Cosman and Vecera, 2012; Yeh and Lin, 2013), and when the relevant and irrelevant information belonged to the same object (Chen, 2003). Other factors such as the number of locations at which a distractor or a target could appear (Marciano and Yeshurun, 2011; Wilson et al., 2011) and the relative salience of a target and distractor (Eltiti et al., 2005) also influenced the degree of distractor processing in ways inconsistent with the perceptual load theory. Together, these results challenge the perceptual load theory. They suggest that perceptual load, instead of being a determinant in distractor processing as proposed by the perceptual load theory, is one of a number of factors that contribute to the degree of distractor processing.

Recently, several researchers (Benoni and Tsal, 2010; Tsal and Benoni, 2010; Wilson et al., 2011) proposed an alternative account of distractor processing. Tsal and Benoni (2010) noted that evidence supporting the perceptual load theory came largely from experiments that manipulated perceptual load via display set size. Because an increase in display set size entails an increase in the number of neutral stimuli, and previous research on Stroop interference has shown that increasing irrelevant stimuli in a Stroop display dilutes Stroop interference (Kahneman and Chajczyk, 1983; Brown et al., 1995), this raises the question whether the reduction in distractor processing in a high perceptual load task is caused by the dilution of distractor interference rather than by the unavailability of perceptual resources. To test their hypothesis, Tsal and Benoni measured distractor interference in three types of displays: the typical low and high perceptual load displays that differed in the number of neutral stimuli, and a new dilution display that had the same number of neutral stimuli as that in the high load display but differed from the high load display in that the target and the neutral stimuli were perceptually segregated by color or spatial location. This segregation made it easy for the neutral stimuli to be ignored, so that the dilution display was low in perceptual load but high in display set size. Contrary to the prediction of the perceptual load theory, no response congruency effect was found in the dilution condition.

Based on this and similar results from other experiments, Tsal and Benoni (2010) proposed a dilution account of distractor processing. According to this account, an incongruent distractor causes interference when its representation is sufficiently strong to enter lexical memory and activate the target-opposite response category. When neutral stimuli, regardless of their task relevancy, are present in a display, their features compete with those of the incongruent distractor, degrading the quality of its representation. When the degraded representation of the distractor is not strong enough to enter lexical memory, there can be little distractor interference. In other words, it is the dilution of distractor interference, not the unavailability of spare perceptual resources that eliminates distractor interference in displays with a large set size.

Wilson et al. (2011) proposed a slightly different dilution account to interpret the display set size effect in distractor processing. They proposed a two-stage model, following from Neisser (1967) and Hoffman (1979): there is an initial parallel processing stage, during which the location most likely to contain the target is selected, and a serial processing 2nd stage, during which the selected item is further processed. Because only one item is processed at a time in the 2nd stage, all the other stimuli in the search array are irrelevant in that stage, and this is so regardless of whether a specific stimulus is task relevant or irrelevant in the 1st stage. Dilution occurs during the 2nd stage if there are sufficient spare resources to process the irrelevant stimuli. Increasing the number of neutral stimuli reduces distractor processing, either because of decreased resources to each stimulus or because of increased crosstalk between the distractor and the neutral stimuli. Thus, like Tsal and Benoni (2010), Wilson et al. attribute the display set size effect to the presence of neutral stimuli, which dilute distractor interference regardless of their task relevancy. They manipulated both the display set size and the number of locations at which a target could appear so that the neutral stimuli were relevant on some trials and not on the other trials. The response congruency effect decreased with increasing display set size, and as they predicted, the reduction was comparable regardless of the relevancy of the neutral stimuli to the task. These results are consistent with the notion that the mere presence of neutral stimuli dilutes distractor interference. Experiment 1 below provides an illustration of some of the main aspects of Wilson et al.'s experiments, and replicates their results.

Wilson et al. (2011) found that the dilution effect was comparable regardless of the cued target locations, but previous research generally shows that the attentional focus modulates the degree of distractor processing. The idea of attentional focus was captured in Eriksen and St. James' (1986) "zoom lens model," and it was described by Cave et al. (2010) as "attentional zoom," and by Wilson et al. as "attentional breadth." Using a spatial cuing paradigm, Yantis and Johnston (1990) reported that presenting a 100% valid cue before the onset of a target could minimize distractor interference in a search display. Paquet and Lortie (1990) also reported that precuing the target location decreased distractor interference when the target and distractors belonged to the same category. Similar results were shown by LaBerge and his colleagues (1991), who demonstrated that narrowing attention focus so that the distractor appeared outside it decreased distractor interference, and by Eriksen and St. James (1986), who found reduced distractor interference when the number of precued locations decreased. In both cases, an incongruent distractor caused less interference when a task induced a relatively small attentional focus that excluded the distractor. Thus, all else being equal, a larger response congruency effect is more likely to be found when an incongruent distractor is inside rather than outside an observer's attentional focus.

Attentional focus has also been shown to mediate the effect of perceptual load on distractor processing. For example, when a 100% valid precue was used to indicate the location of the target, the perceptual load effect was eliminated (Johnson et al., 2002).

The perceptual load effect was also reduced or eliminated when participants were prevented from varying the extent of attentional focus between the low and high load trials, either by intermixing the two types of trials within the same block (Murray and Jones, 2002; Theeuwes et al., 2004) or by designing stimuli so that the relevant and irrelevant information pertained to the same object (Chen, 2003). Furthermore, intertrial analyses showed that distractor interference on a high perceptual load trial was more likely to occur when it was preceded by a low perceptual load trial rather than by a high perceptual load trial (Theeuwes et al., 2004; Biggs and Gibson, 2010). As low perceptual load is more likely to induce a relatively broad attentional focus compared with high perceptual load, the observed intertrial contingency, together with the finding that intermixing trials of different perceptual loads within the same block could reduce or eliminate the perceptual load effect, suggests that different response strategies, with variations in attentional focus, may have played a role in the perceptual load effect found in many previous studies.

The results of recent research underscore the importance of understanding the roles of neutral stimuli and attentional focus, and how they interact to influence distractor processing in visual selection. In Wilson et al. (2011), the magnitude of dilution was comparable regardless of the number of cued target locations. Because the extent of attentional focus should correlate with the cue set size, this result indicates that the extent of attention focus did not affect dilution effects. In other words, in Wilson et al.'s study, whether a stimulus was located inside or outside an observer's attentional focus did not influence the degree of processing of that stimulus. As we discussed in the previous section, this finding conflicts with previous research, which shows that a stimulus receives more processing when it is inside rather than outside one's attentional focus (e.g., Eriksen and St. James, 1986; Yantis and Johnston, 1990; LaBerge et al., 1991).

In Wilson et al. (2011)'s study, the appearance of the target display was marked by onset transients and the total number of stimuli in the target display varied in accordance with the display set size. Abrupt visual onsets attract attention under most circumstances (Yantis and Jonides, 1984, 1990). Consequently, the use of onset transients in Wilson et al.'s experiments could undermine the spatial distribution of attention induced by the cue, resulting in a larger attentional focus when the display set size was large rather than when it was small. This could lead to the comparable dilution effects in both the small and large cue set size conditions in Wilson et al.'s study.

The 4 experiments reported in this study investigated the factors that influence dilution effects. Specifically, we focused on three issues: the role of attentional focus in modulating the effect of display set size on distractor processing, the locus of dilution, and the role of target knowledge in dilution effects. In Experiment 1, we deliberately co-varied display set size with the extent of attentional focus by using luminance increment to signal the appearance of the target display. Our goal was to replicate the findings of Wilson et al. (2011), and we did. The magnitude of the dilution effect was similar regardless of whether 2 or 6 target locations were cued. Experiment 2 used luminance decrement instead of luminance increment so that the stimulus change lowered the contrast rather than raising it, and thus the attentional focus induced by the cue would not be affected very much by the appearance of the target display. A dilution effect was found when the extent of attentional focus was large, but not when it was small. In Experiment 3, we explored the locus of dilution by varying the number of inverted letters in the two display set size conditions. No dilution effects were found, suggesting that dilution occurred beyond a feature level. Finally, in Experiment 4, we tested the effect of preknowledge of the target by making its color predictable for one group of participants but unpredictable for the other group. A dilution effect was found for the latter group, but not for the former one.

EXPERIMENT 1

Experiment 1 was modeled after Wilson et al. (2011) to replicate their results with our modified experimental paradigm, which differed from Wilson et al.'s in that the number of stimuli in the target display was held constant via the use of non-letter place-holders. As in Wilson et al., we manipulated cue set size (CueSize) and display set size (DisplaySize) independently (see **Figure 1**). CueSize refers to the number of possible locations at which a target could appear (2 or 6), and DisplaySize refers to the number of letters in the search array (2 or 6, excluding the critical distractor). Luminance increment was used to signal the appearance of the target display. There was always one target letter present in each display, either an H or an S, and the task was to determine as quickly and as accurately as possible which of the two targets was present. Based on Wilson et al.'s results, we expected our participants to show a dilution effect of similar magnitude in both the 2-cue and 6-cue conditions.

METHOD

Participants

Nineteen undergraduate students from the University of Canterbury volunteered to participate in the experiment. Each was paid NZ$10. All reported to have normal or corrected-to-normal vision.

Apparatus and stimuli

Stimulus displays were shown on a PC with a 16-inch monitor. The participants were tested individually in a dimly lit room. The viewing distance was approximately 60 cm. E-prime 2.0 (Schneider et al., 2002) was used to display stimuli and to record responses.

All stimuli were presented against a black background. Each trial consisted of three displays: the fixation, the cue, and the target display. The fixation display consisted of 7 identical gray (RGB = 60, 60, 60) figure-8 stimuli that also served as place-holders in subsequent displays. Each place-holder subtended 0.86° of visual angle in height and 0.57° in width. While six of them were placed at equal distance along the perimeter of an imaginary circle centered on fixation with a radius of 2.48°, the 7th one was always at fixation. The cue display consisted of four frames. Frames 2 and 4 were identical to the fixation display. Frames 1 and 3 differed in that either a pair of place-holders in opposite locations (in the 2-cue condition) or all six place-holders along the imaginary perimeter (in the 6-cue condition) became white (RGB = 255, 255, 255) instead of remaining to be gray. As

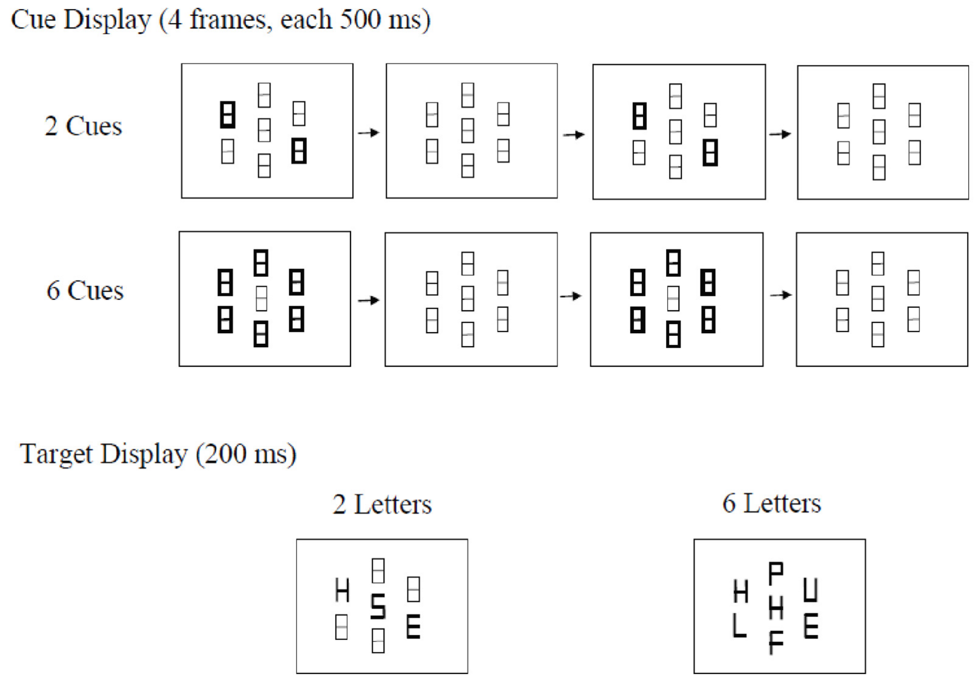

FIGURE 1 | Examples of cue displays and target displays from Experiment 1. The cue display consisted of 4 frames. The locations of the target, which was either an H or an S, were indicated by 2 or 6 figure-8 place-holders increasing in luminance. The target display consisted of 2 letters or 6 letters, excluding the critical distractor, which always appeared at the center. The 2-letter display is an example of an incongruent trial. The 6-letter display is an example of a congruent trial. Note that the appearance of the target display is signaled by luminance increment.

there was no blank screen between the fixation and the cue display or between any two frames in the cue display, the perception of the cue was that of 2 or 6 place-holders flashing twice.

We are using the DisplaySize label to be consistent with Wilson et al. (2011), but when the DisplaySize was 2 in this experiment, there were 4 figure-8 place-holders added to the display, so that the total number of stimuli with the distractor and the place-holders was always 7. Following Yantis and Jonides (1984), the letters, which were white in color (RGB = 255, 255, 255), were constructed by increasing the luminance of the appropriate line segments of the figure-8 stimuli and deleting the unneeded segments. Thus, the letters were created via luminance increment rather than the onset transients used by Wilson et al. The stimulus at fixation was always the critical distractor. It was white, and was equally likely to be an H or an S. In the 6-letter condition, the search array consisted of a target letter (H or S) and 5 neutral letters (P, E, F, L, and U). In the 2-letter condition, the search array consisted of a target (again an H or an S), a neutral letter selected randomly and with equal probability from the set of neutral letters mentioned above, and 4 place-holders identical to those in the fixation display. On half of the trials (the congruent condition), the target and distractor were identical. On the rest of the trials (the incongruent condition), they were different letters associated with different responses.

Design and procedure

The experiment used a 2 × 2 × 2 within-participants design. The principal manipulations were CueSize (2-cue vs. 6-cue), DisplaySize (2-letter vs. 6-letter), and target-distractor Congruency (congruent vs. incongruent). The three factors were varied independently. All types of trials were presented randomly within a block.

Each trial started with the presentation of the fixation display. After 500 ms, either 2 or 6 place-holders along the perimeter of the imaginary circle would flash twice, with each flash lasting for 500 ms, with a 500 ms interval after each flash. At the end of the 2nd interval (i.e., the 4th frame of the cue display), the central place-holder would turn into a letter, as would either 2 or 6 of the other place-holders, depending on the DisplaySize condition. The screen went black after 200 ms. The task was to respond, as quickly and as accurately as possible, whether the target was an H or an S. The participants were instructed to maintain fixation at the central place-holder throughout the duration of a trial, and to use the index and middle fingers of their right hand to press one of the two designated keys on a response box (the 4th key if the target letter was an "H," and the 5th key if it was an "S"). They were explicitly informed that the target would only appear at one of the cued locations and that the center letter was always a distractor that they should try to ignore. The entire experiment consisted of 2 blocks of 16 practice trials, followed by 5 blocks of 96 experimental trials with short breaks after each block. It took about 35 min to complete the experiment.

RESULTS

Table 1 shows the mean reaction times (RTs) for correct responses and the error rates, and the graph in **Figure 2** shows the

Table 1 | Experiment 1: mean reaction times and error rates as a function of cue set size, display set size, and target-distractor congruency.

Display set size	Cue set size			
	2-cue		6-cue	
	C	*I*	*C*	*I*
REACTION TIMES (ms)				
2-letter	604 (22)	654 (23)	635 (22)	722 (26)
6-letter	663 (34)	697 (31)	806 (27)	874 (35)
ERROR RATES (% INCORRECT)				
2-letter	2.2 (0.6)	4.7 (0.9)	3.7 (0.8)	7.0 (1.5)
6-letter	6.7 (1.1)	6.0 (1.1)	13.3 (1.7)	12.4 (1.9)

Standard errors are in the parentheses. C, Congruent; I, Incongruent.

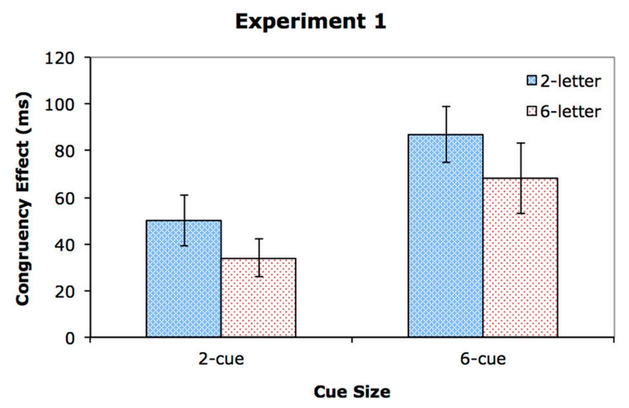

FIGURE 2 | The congruency effect (incongruent RT–congruent RT) across the different conditions of Experiment 1. Error bars show the standard error of the mean.

congruency effect across conditions[1]. One participant's data were not included due to high error rates (greater than 40% in one condition). A 2 × 2 × 2 repeated measures analysis of variance (ANOVA) was conducted on RTs. (See **Table 2** for details of the results). All the main effects were significant. The participants were faster in the 2-cue condition (655 ms) than in the 6-cue condition (759 ms), $p < 0.001$. They were also faster when the display consisted of two letters (654 ms) instead of six letters (760 ms), $p < 0.001$, and when the target and distractors were congruent (677 ms) rather than incongruent (737 ms), $p < 0.001$. CueSize interacted with DisplaySize, $p < 0.001$, suggesting that RT increased more dramatically from the 2-letter condition to the 6-letter condition on the 6-cue trials (an increase of 162 ms) than on the 2-cue trials (an increase of 51 ms). CueSize also interacted with Congruency, $p < 0.02$. The congruency effect was larger in the 6-cue condition (78 ms) than in the 2-cue condition (42 ms), indicating a positive relationship between the number of target locations and the degree of distractor processing. Furthermore, a dilution effect was found, as evidenced by the significant interaction between DisplaySize and Congruency, $p < 0.02$, suggesting a larger congruency effect in the 2-letter condition (69 ms) than in the 6-letter condition (51 ms). Finally, there was no significant three-way interaction of CueSize, DisplaySize, and Congruency. The last result indicated that the magnitude of the dilution effect was independent of the cue set size, as can be seen in **Figure 2**.

A similar ANOVA was conducted on the error rates. (See **Table 3** for details of the results). Consistent with the RT results, error rates were lower in the 2-cue condition (4.9%) than in the 6-cue condition (9.1%), $p < 0.001$, and on the 2-letter trials (4.4%) than on the 6-letter trials (9.6%), $p < 0.001$. CueSize interacted with DisplaySize, $p < 0.02$, suggesting a larger increase in error rate from the 2-letter to 6-letter condition on the 6-cue trials (an increase of 7.5%) compared with the 2-cue trials (an increase of 2.9%). Finally, there was a significant interaction between DisplaySize and Congruency, $p < 0.02$. Whereas a significant congruency effect was found on the 2-letter trials (2.9% error rate), a similar effect was not found on the 6-letter trials (−0.8% error rate). No other effects reached significance. There was no indication of any speed-accuracy tradeoff.

DISCUSSION

The results of Experiment 1 were remarkably similar to those of Wilson et al. (2011). In both cases, the congruency effect was substantially larger in the 6-cue condition than in the 2-cue condition. As they pointed out, this result is inconsistent with the perceptual load theory, which predicts a decrease in distractor interference with increasing cue set size, because perceptual load would increase with the number of locations at which a target could appear. Indeed, if RT is a valid indicator of perceptual load, then the longer RT in the 6-cue than the 2-cue condition provides evidence for the higher perceptual load in the former than in the latter. The fact that the perceptual load effect was reversed across the cue conditions is incompatible with the perceptual load theory.

The larger congruency effect in the 6-cue condition was likely caused by the increased RT in that condition compared with the 2-cue condition. As the cue in the 6-cue condition would induce a broader attentional focus than the cue in the 2-cue condition, more irrelevant letters would be within the attentional focus in the former condition, resulting in longer response latencies to the target. Previous research has shown a positive link between the processing time of a target and the magnitude of the congruency effect, and it has been proposed that an increase in the processing time of a target increases the window of opportunity for distractor intrusion, resulting in increased distractor processing (Lavie and De Fockert, 2003; Tsal and Benoni, 2010; Wilson et al., 2011). We agree with this view, and attribute the differential congruency effects in the two cue size conditions to the longer response latencies in the 6-cue condition relative to the 2-cue condition.

As in Wilson et al. (2011), we found that the congruency effect was more diluted when there were more letters in the display, and more importantly, the degree of dilution was comparable in both the 2-cue and 6-cue conditions. However, as we discussed before, the luminance increment that was used to signal the appearance

[1]In all experiments, response latencies greater than 2000 ms were excluded. These constituted less than 1% of the total data in each experiment. Only trials that were correct were included in the tables and the statistical analyses.

Table 2 | Results of statistical analyses of the reaction times in Experiments 1, 2, and 3.

	Reaction times								
	Experiment 1			Experiment 2			Experiment 3		
	$F_{(1, 17)}$	p	η_p^2	$F_{(1, 19)}$	p	η_p^2	$F_{(1,15)}$	p	η_p^2
Cue	34.82***	0.001	0.67	124.85***	0.001	0.87	174.00***	0.001	0.92
Display	73.48***	0.001	0.81	90.02***	0.001	0.83	77.63***	0.001	0.84
Cong	64.77***	0.001	0.79	58.76***	0.001	0.76	48.93***	0.001	0.77
Cue*Display	25.36***	0.001	0.60	60.74***	0.001	0.76	54.58***	0.001	0.78
Cue*Cong	6.87*	0.02	0.29	16.14***	0.001	0.46	24.70***	0.001	0.62
Display*Cong	6.94*	0.02	0.29	3.00	0.10	0.14	0.02	0.89	0.01
Cue*Display*Cong	0.03	0.86	0.01	9.44**	0.01	0.33	0.06	0.81	0.01

Cue, CueSize; Display, DisplaySize; Cong, Congruency.
$^*p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

Table 3 | Results of statistical analyses of the error rates in Experiments 1, 2, and 3.

	Error rates								
	Experiment 1			Experiment 2			Experiment 3		
	$F_{(1, 17)}$	p	η_p^2	$F_{(1, 19)}$	p	η_p^2	$F_{(1, 15)}$	p	η_p^2
Cue	27.09***	0.001	0.61	52.68***	0.001	0.73	57.21***	0.001	0.79
Display	36.96***	0.001	0.68	69.07***	0.001	0.78	28.30***	0.001	0.65
Cong	1.85	0.19	0.10	7.77*	0.02	0.29	6.85*	0.02	0.31
Cue*Display	7.04*	0.02	0.29	79.22***	0.001	0.81	16.85***	0.001	0.53
Cue*Cong	0.07	0.80	0.01	2.24	0.15	0.11	2.41	0.14	0.14
Display*Cong	7.99*	0.01	0.32	0.10	0.75	0.01	0.01	0.95	0.01
Cue*Display*Cong	0.18	0.68	0.01	0.12	0.73	0.01	0.04	0.84	0.01

Cue, CueSize; Display, DisplaySize; Cong, Congruency.
$^*p < 0.05$; $^{***}p < 0.001$.

of the target display in the present experiment, which is similar to the onset transient used in Wilson et al.'s (2011) experiments, could change the extent of attentional focus, raising doubts about the ability to measure the effects of perceptual load and dilution. In Experiment 2, we addressed this issue by using luminance decrement instead of luminance increment to minimize the effect of stimulus appearance on the extent of attentional focus induced by the cue.

EXPERIMENT 2

In Experiment 2, we replaced luminance increment with luminance decrement so that the target locations in the cue display and the appearance of the letters in the target display were both signaled via luminance decrease instead of luminance increase (see **Figure 3**). Because luminance decrement is less likely to capture attention than luminance increment (Yantis and Jonides, 1984), the appearance of the target display should be less likely to affect the extent of attentional focus induced by the cue, allowing the attentional focus to be determined more by the manipulation in CueSize.

As our selective review of the literature in the previous section indicates (e.g., Paquet and Lortie, 1990; Paquet and Craig, 1997; Johnson et al., 2002), there is reason to believe that the effect of neutral stimuli on distractor processing could be strongly affected in this paradigm by their locations relative to the attentional focus. As stimuli are likely to be processed at a greater extent when they are inside rather than outside one's attentional focus, we predicted a larger dilution effect in the 6-cue condition compared with the 2-cue condition, for more neutral letters should fall inside the participants' attentional focus in the former than in the latter.

METHOD

The method of Experiment 2 was the same as that in Experiment 1 except for the following differences. First, the place-holders in the fixation display were white instead of gray. Second, target locations were indicated by luminance decrement instead of luminance increment in the cue display. Frames 2 and 4 were identical to the fixation display, i.e., all the place-holders were white. This ensured that compared with the participants in Experiment 1, those in Experiment 2 were less likely to expand their attentional focus upon the onset of the target display in the 2-cue condition, for the appearance of the target display was signaled by luminance decrement instead of luminance increment. Frames 1 and 3 differed from the fixation display in that the 2 or 6 place-holders in the cued locations were gray. Thus, the perception of the cue was that of 2 or 6 place-holders dimming twice. Third, in the target display, all the stimuli were white regardless of whether they

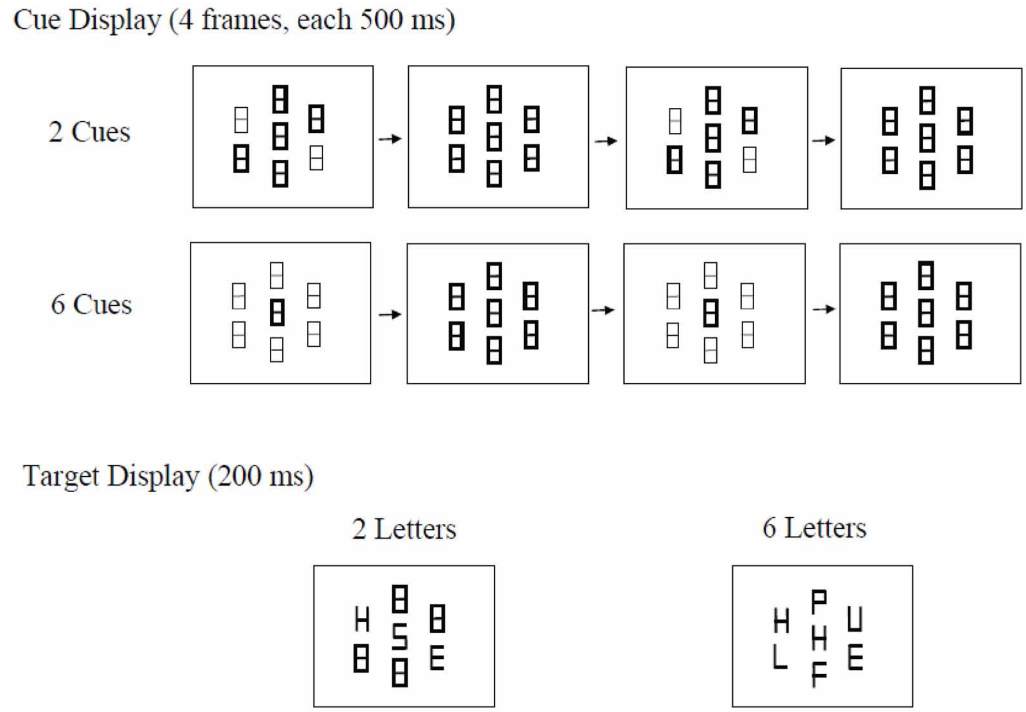

FIGURE 3 | Examples of cue displays and target displays from Experiment 2. Note that the appearance of the target display is signaled by luminance decrement.

were letters or place-holders. These design features ensured that there was minimal difference in luminance from the last frame of the cue to the target display, or between the target displays in the 2-letter and 6-letter conditions. Twenty new participants took part in the experiment.

RESULTS

Table 4 shows the mean RTs and error rates, and **Figure 4** shows the effects of congruency. Two repeated measures ANOVAs were conducted, one on the RT data (see **Table 2**), and the other on the error rates (see **Table 3**). As in Experiment 1, all the three main effects were significant. The participants were faster and more accurate in the 2-cue condition (613 ms with 5.7% error rate) than in the 6-cue condition (757 ms with 11.5% error rate), $p < 0.001$, for both RT and error rates. They were also faster and more accurate in the 2-letter condition (653 ms with 6.3% error rate) than in the 6-letter condition (717 ms with 10.9% error rate), $p < 0.001$ in both cases. In addition, performance was better on congruent trials (659 ms with 7.2% error rate) than on incongruent trials (711 ms with 10.1% error rate), $p < 0.001$ for RT; and $p < 0.02$ for error rates. CueSize interacted with DisplaySize, both in RT, $p < 0.001$, and in error rates, $p < 0.001$, suggesting that an increase in display set size impaired performance more when the target could appear at 1 of 6 locations (an increase of 115 ms and 8.8% error rate) rather than at 1 of 2 locations (an increase of 14 ms and 0.5% error rate). In RT, the magnitude of the congruency effect was again affected by CueSize, $p < 0.001$. The congruency effect was larger in the 6-cue condition (73 ms) than in the 2-cue condition (31 ms). Finally, there was a significant three-way interaction in RT, $p < 0.01$, which is illustrated in **Figure 4**. No other effects reached significance.

Table 4 | Experiment 2: mean reaction times and error rates as a function of cue set size, display set size, and target-distractor congruency.

Display set size	Cue set size			
	2-cue		6-cue	
	C	*I*	*C*	*I*
REACTION TIMES (ms)				
2-letter	595 (26)	617 (25)	651 (31)	747 (35)
6-letter	600 (25)	640 (26)	789 (41)	839 (38)
ERROR RATES (% INCORRECT)				
2-letter	4.4 (0.9)	6.6 (1.2)	5.2 (0.8)	9.1 (1.4)
6-letter	5.2 (1.0)	6.7 (1.1)	13.9 (1.6)	17.9 (1.8)

C, Congruent; I, Incongruent. Standard errors are in the parentheses.

To clarify the Three-Way interaction, we conducted two separate ANOVAs, one for the data in the 2-cue condition and the other for the data in the 6-cue condition. In the 6-cue condition, all the effects were significant. RT was longer in the 6-letter condition (814 ms) than in the 2-letter condition (699 ms), $F_{(1,\ 19)} = 80.65$, $MS_e = 3238$, $p < 0.001$, $\eta_p^2 = 0.81$, and on incongruent (793 ms) than congruent (720 ms) trials, $F_{(1,\ 19)} = 53.88$, $MS_e = 1988$, $p < 0.001$, $\eta_p^2 = 0.74$. DisplaySize interacted with

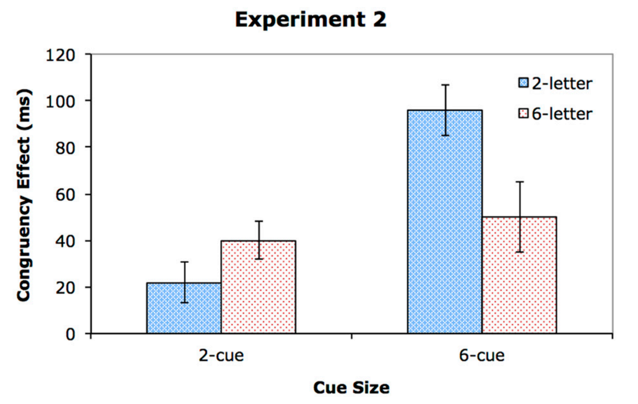

FIGURE 4 | The congruency effect for Experiment 2.

Congruency, $F_{(1,\ 19)} = 7.58$, $MS_e = 1404$, $p < 0.02$, $\eta_p^2 = 0.29$. The congruency effect was larger in the 2-letter condition (96 ms) than in the 6-letter condition (50 ms), indicating a significant dilution or perceptual load effect.

The pattern of data differed in the 2-cue condition. The main effects of DisplaySize and Congruency were both significant, with faster RT on the 2-letter trials (606 ms) than on the 6-letter trials (620 ms), $F_{(1,\ 19)} = 16.21$, $MS_e = 247$, $p < 0.001$, $\eta_p^2 = 0.46$, and on the congruent trials (598 ms) than on the incongruent trials (629 ms), $F_{(1,\ 19)} = 20.11$, $MS_e = 960$, $p < 0.001$, $\eta_p^2 = 0.51$. The interaction between DisplaySize and Congruency was marginally significant, $F_{(1,\ 19)} = 4.04$, $MS_e = 360$, $p = 0.06$, $\eta_p^2 = 0.18$. Importantly, the direction of the interaction was opposite to what was found in Experiment 1: the congruency effect was larger in the 6-letter condition (40 ms) than in the 2-letter condition (22 ms). Thus, there was no evidence of a dilution effect when the neutral letters were outside the attentional focus in the 2-cue condition.

To confirm statistically that the pattern of data in Experiment 1 differed from that in Experiment 2, we conducted a combined analysis of the RT data across the two experiments, using a mixed ANOVA with Experiment as a between-subjects factor and CueSize, DisplaySize, and Congruency as within-subjects factors. For the sake of brevity, we report only the significant interactions with Experiment, of which there were two. One was a significant interaction between DisplaySize and Experiment, $F_{(1,\ 36)} = 9.38$, $MS_e = 3582$, $p < 0.01$, $\eta_p^2 = 0.21$, suggesting that the increase in RT from the 2-letter to 6-letter condition was larger in Experiment 1 (an increase of 106 ms) than in Experiment 2 (an increase of 65 ms). The second was a significant four-way interaction, $F_{(1,\ 36)} = 4.49$, $MS_e = 946$, $p < 0.05$, $\eta_p^2 = 0.11$. Subsequent analyses on the 2-cue and 6-cue trials separately indicated that the 4-way interaction arose primarily from the participants in the two experiments behaving differently in the 2-cue condition, where a significant 3-way interaction of DisplaySize, Congruency, and Experiment was found, $F_{(1,\ 36)} = 5.56$, $MS_e = 473$, $p < 0.05$, $\eta_p^2 = 0.13$. A similar 3-way interaction was not found in the 6-cue condition, $F_{(1,\ 36)} = 1.59$, $MS_e = 1042$, $p = 0.21$, $\eta_p^2 = 0.04$. These results confirmed that the pattern of data in Experiments 1 and 2 differed when the cue set size was 2, but not when it was 6.

DISCUSSION

The results of Experiment 2 suggest that the extent of attentional focus modulates the effect of display set size on distractor processing. In the 6-cue condition, the target was equally likely to appear at any location in the search array. To find the target quickly, the best strategy would be to adopt a relatively broad attentional focus that would include the entire target display, including the neutral stimuli. As the neutral stimuli were within the attentional focus, they would compete with the critical distractor for representation. Hence, a dilution effect was found in the 6-cue condition. In contrast, in the 2-cue condition, the participants' attention was likely to be more narrowly focused, and unlike Experiment 1, there was no abrupt luminance increment to draw attention more widely when the target array appeared. As the letters that appeared at the uncued locations were largely outside the focus of attention, they would not receive the same kind of processing as their counterparts in the 6-cue condition. Whatever processing these letters might have received due to attentional leakage, the level of processing was not sufficient to interfere with the representation of the distractor. As a result, increasing display set size in the 2-cue condition did not lead to a dilution effect.

It is worth noting that the participants in the 2-cue condition of Experiment 2 took longer to respond to the target on the 6-letter trials than on the 2-letter trials despite the fact that the participants knew in advance that the target would never occur at an uncued location. The increased RT in the 6-letter trials indicated that attention could not completely filter out all the irrelevant information. This result is in line with the view that attentional selection is often incomplete, and that some processing can still happen to irrelevant stimuli even with clear spatial separation between a target and irrelevant distractors (Treisman, 1964; Miller, 1991).

Another interesting aspect of Experiment 2's data is the reversed dilution effect in the 2-cue condition. The congruency effect was larger, instead of smaller, when the display consisted of 6 letters rather than 2 letters. It is notable that RT was substantially longer on the 6-letter trials compared with the 2-letter trials. As we discussed in Experiment 1, an increase in response latencies increases the window of opportunity for distractor intrusion. As a result, congruency effect was larger in the 6-letter condition than in the 2-letter condition.

EXPERIMENT 3

As mentioned earlier, several researchers have proposed a dilution account to interpret the reduction in distractor interference with increasing display set size (Benoni and Tsal, 2010; Tsal and Benoni, 2010; Wilson et al., 2011). Because stimuli of the same category, which share both basic features and response code, were used in these prior studies, the proposed dilution accounts emphasize competition between the features of the added display items and the features of the distractor, which degrades the quality of the distractor representation (e.g., Tsal and Benoni, 2010). In other words, they suggest that dilution occurs at a feature level.

Experiment 3 was designed to test this notion empirically. In Experiment 3, both the 2-item and 6-item conditions had 2 upright letters present in the target array, but in the 6-item condition, there were also 4 inverted letters. Because the inverted letters shared basic features but not meaning with the critical distractor, this design allowed us to assess the effect of neutral stimuli on distractor processing at a feature level. If dilution occurs at a feature level, the participants in Experiment 3 should show the same pattern of result as that in Experiment 2. Conversely, if dilution occurs at a level beyond feature processing (e.g., at a categorical, semantic, or response level), no dilution effects should be found in the 6-item condition.

METHOD

The method of Experiment 3 was identical to that of Experiment 2 except for the stimuli in the large display set size condition. Instead of 6 letters, the search array consisted of 2 upright letters (i.e., the target and a neutral letter selected randomly on each trial from the set of neutral stimuli as in Experiment 2) and 4 inverted letters constructed from the original set of neutral letters (i.e., P, F, U, L, E) with a 180 degree rotation. As before, we varied the cue set size (the 2-cue and 6-cue conditions) independently of the display set size (the 2-item and 6-item conditions). Sixteen new participants volunteered for the experiment.

RESULTS

Table 5 shows the response times and error rates, and **Figure 5** shows the congruency effects. As before, we conducted two separate repeated-measures ANOVAs, one on the RT data (see **Table 2**), and the other on the error rates (see **Table 3**). The participants were again faster and more accurate in the 2-cue condition (615 ms with 4.8% error rate) than in the 6-cue condition (761 ms with 11.5% error rate), $p < 0.001$ for both RT and accuracy. They were also faster and more accurate when the display set size was 2 (660 ms with 6.0% error rate) rather than 6 (715 ms with 10.2% error rate), $p < 0.001$ in both cases. In addition, responses were faster and more accurate on congruent trials (664 ms with 7.1% error rate) than on incongruent trials (712 ms with 9.1% error rate), $p < 0.001$ for RT, and $p < 0.02$ for accuracy. The interaction between CueSize and DisplaySize was also significant, $p < 0.001$ for RT and accuracy. This suggests that once again, an increase in display set size impaired performance more in the 6-cue condition (an increase of 105 ms and 8% error rate) compared with the 2-cue condition (an increase of only 6 ms and 0.4% error rate). CueSize interacted with Congruency in RT, $p < 0.001$, indicating a larger congruency effect in the 6-cue condition (71 ms) than in the 2-cue condition (26 ms). Importantly, neither the two-way interaction between DisplaySize and Congruency nor the 3-way interaction of CueSize, DisplaySize and Congruency was significant, $F_{(1,15)} < 1$, *ns*. in both cases. These results indicate that the presence of the inverted letters had a negligible effect on the degree of distractor interference regardless of whether the cue set size was 2 or 6. No other effects reached significance, and there was no evidence of a speed-accuracy tradeoff.

A combined analysis across Experiments 2 and 3 was conducted on the RT data to verify that the pattern of data in the two experiments differed significantly. Again, for the sake of brevity, we report only the significant interactions that involve Experiment. The only significant effect was the four-way interaction of CueSize, DisplaySize, Congruency, and Experiment, $F_{(1,\ 34)} = 6.12$, $MS_e = 819$, $p < 0.05$, $\eta_p^2 = 0.15$. Separate analyses on the 2-cue and 6-cue trials confirmed that the four-way interaction in the original analysis arose from the 6-cue condition, where a significant three-way interaction of DisplaySize × Congruency × Experiment was found, $F_{(1,\ 34)} = 4.95$, $MS_e = 1086$, $p < 0.05$, $\eta_p^2 = 0.13$. A similar effect was not found in the 2-cue condition, $F_{(1,\ 34)} = 2.0$, $MS_e = 356$, $p = 0.17$, $\eta_p^2 = 0.06$. These results suggest that the effect of neutral stimuli on distractor processing differed in the 6-cue condition between Experiments 2 and 3.

DISCUSSION

The most important finding of Experiment 3 was the elimination of the dilution effect in the 6-cue condition. Adding inverted letters to the display did not lower the distractor interference in this condition, even though the upright letters added to displays in the same condition of Experiments 1 and 2 lowered the

Table 5 | Experiment 3: mean reaction times and error rates as a function of cue set size, display set size, and target-distractor congruency.

Display set size	Cue set size			
	2-cue		6-cue	
	C	*I*	*C*	*I*
REACTION TIMES (ms)				
2-item	599 (29)	625 (31)	674 (35)	743 (34)
6-item	605 (31)	630 (33)	777 (33)	849 (38)
ERROR RATES (% INCORRECT)				
2-item	4.1 (0.7)	5.0 (1.0)	5.8 (1.0)	9.1 (1.5)
6-item	4.4 (0.9)	5.5 (1.5)	14.0 (1.6)	16.9 (2.4)

Standard errors are in the parentheses. C, Congruent; I, Incongruent.

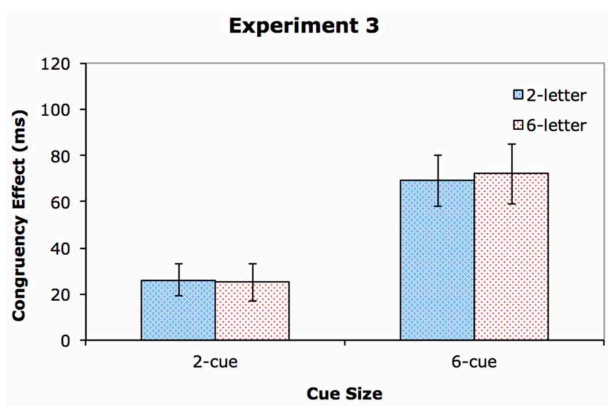

FIGURE 5 | The congruency effect for Experiment 3.

distractor interference in those experiments. This result suggests that the inverted letters in the 6-item condition had a negligible effect on the degree of distractor processing, despite the fact that they increased the overall RT to the target. This RT increase likely reflects the extra difficulty in locating the target due to the increased similarity between the target and the relevant items in the search array. Previous research has shown that an increase in similarity between a target and distractors impairs segmentation, making it hard to distinguish the target from the distractors (Duncan and Humphreys, 1989, 1992). Thus, these items that have been added to the display, which share features with the target and the critical distractor but do not activate responses in the same category, can delay the response to the target but do not necessarily degrade the representation of the distractor.

The absence of a dilution effect in Experiment 3 also suggests that the locus of dilution in Experiments 1 and 2 probably occurred at a semantic level. That said, caution must be taken in generalizing this result to other experimental paradigms. It is quite possible that the locus of dilution depends on participants' behavioral goals. When a task requires a categorical or semantic level of processing, dilution may occur at these levels. However, when a task requires a feature level of processing, dilution may occur at the feature level. In the present study, although the two target letters could be distinguished on the basis of basic features, they were referred to as individual letters H and S. Naming the letters would likely induce the participants to code them at a semantic level, differentiating them from the inverted letters in terms of task relevancy and avoiding dilution from the inverted letters in the 6-cue condition.

EXPERIMENT 4

Experiment 3 showed that dilution effects could be eliminated when neutral stimuli did not share the same response code as the target and distractor. In Experiment 4, we investigated whether dilution effects could also be eliminated when participants had preknowledge of the target color. We reasoned that knowing the color of the target in advance would enable participants to use that information to direct their attention to those stimuli that had the task relevant color, thereby excluding the stimuli that had the task irrelevant color from the attention focus. Consequently, if the additional neutral letters in the 6-letter display had a task irrelevant color, they should not affect the degree of distractor processing even when all the locations in the search array were cued in the 6-cue condition. To test this hypothesis, the participants were divided into two groups in Experiment 4. One group (the predictable group) knew in advance the color of the target on each trial. The target was red in one block, and green in a different block. The other group (the unpredictable group) had no preknowledge of the target color on a given trial. The target was equally likely to be red or green. On all trials, 6 locations were cued. If a dilution effect was found in the unpredictable group but not in the predictable group, this would provide additional evidence that the extent of attentional focus modulates dilution effects.

METHOD

The method was similar to that of Experiment 2 except for the following differences. First, as dilution was found only when participants adopted a relatively wide attentional focus, Experiment 4 included only the 6-cue condition. Second, the stimuli in the target display were either red (RGB = 255, 64, 64) or green (RGB = 64, 255, 64). In all conditions, the target had the same color as only one other stimulus: the neutral letter at its opposite location. In other words, the target display consisted of either 2 red and 5 green stimuli, or 2 green and 5 red stimuli. Finally, the participants were randomly and equally divided into two groups. For the predictable group, the color of the target was the same throughout the trials within a block. Half of them completed the red block before the green one, and the order of the blocks was reversed for the other half. For the unpredictable group, the color of the target was unknown on a given trial. The target was equally likely to be red or green within a block. Twenty new participants took part in the experiment.

RESULTS

The data from one participant in the predictable group was excluded from analyses due to high error rates (averaged over 20% across all conditions). **Table 6** shows the response times and error rates, and **Figure 6** shows the congruency effects. A mixed ANOVA with DisplaySize and Congruency as within-subjects

Table 6 | Experiment 4: mean reaction times and error rates as a function of the preknowledge of the target color, display set size, and target-distractor congruency.

Display set size	Target color			
	Predictable		Unpredictable	
	C	*I*	*C*	*I*
REACTION TIMES (ms)				
2-letter	568 (27)	585 (26)	666 (32)	702 (32)
6-letter	574 (29)	595 (25)	713 (38)	721 (32)
ERROR RATES (% INCORRECT)				
2-letter	3.3 (1.2)	2.9 (0.6)	7.1 (1.1)	6.8 (1.4)
6-letter	3.7 (0.7)	4.1 (0.7)	8.5 (1.2)	10.0 (1.4)

Standard errors are in the parentheses. C, Congruent; I, Incongruent.

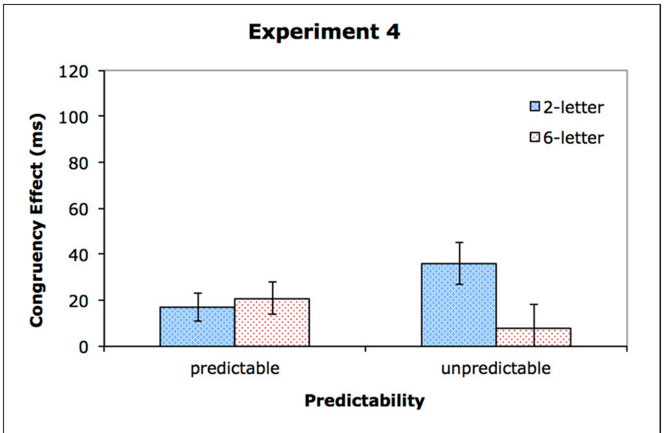

FIGURE 6 | The congruency effect for Experiment 4.

Table 7 | Results of statistical analysis of the reaction times and error rates in Experiment 4.

	Reaction times			Error rates		
	$F_{(1, 17)}$	p	η_p^2	$F_{(1, 17)}$	p	η_p^2
Group	7.83*	0.02	0.32	12.30**	0.01	0.42
Display	22.72***	0.001	0.57	8.02*	0.02	0.32
Display*Group	9.17**	0.01	0.35	1.80	0.20	0.10
Cong	15.42***	0.001	0.48	0.34	0.57	0.02
Cong*Group	0.09	0.77	0.01	0.46	0.51	0.03
Display*Cong	4.26	0.06	0.20	1.93	0.18	0.10
Display*Cong*Group	7.86*	0.02	0.32	0.32	0.58	0.02

Display, DisplaySize; Cong, Congruency.
**p < 0.05; **p < 0.01; ***p < 0.001.*

factors and Group as a between-subjects factor was performed on the RT data (see **Table 7**). The results show that RT was faster in the predictable group (581 ms) than in the unpredictable group (701 ms), $p < 0.05$, indicating that knowing the target color in advance facilitated target responses. As in previous experiments, RT was faster in the 2-letter condition (630 ms) than in the 6-letter condition (651 ms), $p < 0.001$, and in the congruent condition (630 ms) than in the incongruent condition (651 ms), $p < 0.01$. DisplaySize interacted with Group, $p < 0.01$, suggesting a larger set size effect for the unpredictable group (an increase of 33 ms) than for the predictable group (an increase of 8 ms). In addition, there was a significant three-way interaction of DisplaySize, Congruency, and Group, $p < 0.05$, which is illustrated in **Figure 6**.

To clarify the three-way interaction, two separate ANOVAs, one for each group, were performed. For the predictable group, while the main effect of congruency was significant, $F_{(1, 8)} = 10.68$, $MS_e = 298$, $p < 0.05$, $\eta_p^2 = 0.57$, neither the effect of DisplaySize nor its interaction with Congruency reached significant, $p > 0.1$ in both cases. The predictable group thus showed no evidence of a dilution effect. For the unpredictable group, in addition to the main effects of congruency, $F_{(1, 9)} = 6.88$, $MS_e = 696$, $p < 0.05$, $\eta_p^2 = 0.43$, and DisplaySize, $F_{(1, 9)} = 22.21$, $MS_e = 508$, $p < 0.01$, $\eta_p^2 = 0.71$, there was a significant interaction between the two factors, $F_{(1, 9)} = 10.73$, $MS_e = 175$, $p < 0.01$, $\eta_p^2 = 0.54$, with a larger congruency effect in the 2-letter condition (36 ms) than in the 6-letter condition (8 ms), suggesting dilution.

A mixed ANOVA was also performed on the error rates (see **Table 7**). Consistent with the RT results, responses were more accurate in the predictable group (3.5% error rate) than in the unpredictable group (8.1% error rate), $p < 0.01$, and on the 2-letter trials (5% error rate) than on the 6-letter trials (6.6% error rate), $p < 0.05$. No other results were significant.

DISCUSSION

The most important finding of Experiment 4 was that preknowledge of the target color could eliminate dilution effects. Whereas a dilution effect was found when participants had no advanced knowledge of the target color, the effect was negligible when the target color was predictable on a given trial. These results are consistent with the notion that attentional focus modulates the effect of display set size on distractor processing. When the color of the target was known in advance, the participants could use this knowledge to deploy attention efficiently. Thus, even though the attentional focus induced by the cue was wide enough to include all the stimuli, the preknowledge of the target color would allow the participants to locate the task relevant color quickly and to adjust their attentional focus accordingly. This means that the neutral letters with the task irrelevant color could be excluded from the attentional focus fairly early in the process, thereby minimizing their effect on distractor processing.

In contrast, the participants in the unpredictable group did not know the target color in advance. For them to use color to guide attention, they would have to first ascertain the task relevant color by determining which color was the minority color and which one was the majority color, which would probably take some time. As attention could not be zoomed in to the target quickly, the irrelevant letters had more opportunity to be processed, resulting in the dilution effect in the unpredictable group.

It is worth noting that although the distractor differed from the target in both color and location, this perceptual segregation did not completely shield the distractor from being processed, as evidenced by the significant congruency effect in both the predictable and unpredictable groups. This distractor interference suggests that the attentional focus included the distractor along with the two cued locations on either side of it[2]. A similar result was reported by Harms and Bundesen (1983), who found a significant response congruency effect despite the fact that the target and distractors differed in both color and spatial locations.

Tsal and Benoni (2010, Experiment 3) have also investigated the effect of preknowledge of the target color on distractor processing. In two of their experimental conditions most relevant to the present experiment, i.e., the high load and dilution conditions, Tsal and Benoni's participants saw multi-stimulus displays that consisted of letters of different colors. Whereas the color of the target was unknown on a given trial in the high load condition, it was known in advance in the dilution condition. Although the average RT was substantially slower in the high load condition than in the dilution condition, no congruency effect was found in either condition. In contrast, a significant congruency effect was found in the low load condition, in which the target display consisted of a single colored target letter and one distractor. Similar results were found by Benoni and Tsal (2010, Experiment 2). Once again, no significant congruency effects were found in either the high load or dilution condition, but only in the two low load conditions. (The two conditions differed in that the color of

[2]Although our study was not designed to test the issue of attentional selection over contiguous vs. non-contiguous regions, there is evidence that either type of selection may occur under the right circumstances (see Jans et al., 2010; and Cave et al., 2010, for a review). The fact that we found substantial congruency effects in all our experiments despite the positional certainty of the distractor indicates that attention selected contiguous regions in the present experimental paradigm.

the target was known in one condition but not in the other condition). These results confirmed the researchers' hypothesis that perceptual load did not influence the degree of distractor processing when the number of neutral items was held constant. Based on their results, Benoni and Tsal also concluded that whereas preknowledge of target location affects both target and distractor processing, preknowledge of target color affects only target processing.

In Experiment 4 of the present study, the pattern of data between the predictable and unpredictable groups differed not only in the overall response latencies to the target (longer in the unpredictable than the predictable group), but also in the effect of display set size on distractor processing. Whereas the magnitude of the congruency effect decreased with an increase in display set size in the unpredictable group, there was no evidence that display set size influenced the degree of distractor processing in the predictable group. These results suggest that preknowledge of the target color affected both target and distractor processing in our paradigm. However, because of the many differences in methodology between the present experiment and the experiments of Benoni and Tsal (2010) and Tsal and Benoni (2010), we do not consider our results contradictory to their claim. Our results simply show that under some conditions, preknowledge of target color can affect participants' deployment of attention, which in turn can influence the degree of distractor processing.

GENERAL DISCUSSION

These experiments, and the earlier experiments that they build on, illustrate the complexity of visual processing in multi-element displays with targets and distractors. Attention can select the targets once they are identified, but in many cases it cannot prevent the distractors from being partially processed and interfering with the target. This small bit of processing accorded to the distractor is not guaranteed, however; it can be blocked if extra items are added to the display. The current experiments show that these extra items are themselves subject to changes in attentional allocation triggered by sudden luminance increment and by expectations about target color.

Sorting out these different effects will require an understanding of the different factors governing distractor processing in complex displays. One key question in recent years has been why the interference from an irrelevant distractor diminishes when more items are added to the display. The original perceptual load theory posited that these extra items required processing as part of the task, which took processing resources away from the distractor. However, experiments by Tsal and Benoni (2010) and by Wilson et al. (2011) showed that the extra items can weaken distractor interference even when they are easily identified as irrelevant to the task. They described the effect as dilution, because the mere presence of these items diluted the interfering effects of the distractor, independent of their relevance to the task.

Wilson et al. (2011) explained dilution within a two-stage account in the style of Neisser (1967) and Hoffman (1979), with the dilution occurring in the second stage, after the target has been identified and selected. In this account, any processing resources not used by the target are allocated to the non-target items, but unlike Lavie's account, these non-target items are all equal in that their original relevance to the task does not affect their processing. The more non-target items there are, the more interference each item encounters.

Wilson et al.'s (2011) account predicts that Experiment 2 should show dilution in the 2-cue condition; when extra items are present in the 6-letter display, they should decrease the distractor interference relative to the 2-letter display. Instead, the luminance-decrement items in Experiment 2 do not dilute the effects of the distractor, demonstrating that dilution in this paradigm depends on the attentional effects of the display onsets. All items do not contribute equally to dilution; it depends on whether they benefit from the attentional focus or not. These results are consistent with prior research showing that inducing participants to adopt a small attentional focus so that distractors fall outside it could minimize distractor interference in a search display (e.g., Eriksen and St. James, 1986; Yantis and Johnston, 1990; LaBerge et al., 1991). They are also consistent with the more recent finding that singletons capture attention when they are inside but not outside the attentional focus (Belopolsky et al., 2007; Belopolsky and Theeuwes, 2010).

The effects of attention are also seen in Experiment 4, in which dilution from the non-targets is eliminated if their color makes it easy to ignore them. The two types of attentional effects on dilution shown in these experiments are consistent with Yeh and Lin's (2013) demonstration that dilution is affected by perceptual grouping. One option for explaining both sets of results is to modify the dilution account to allow for attentional effects on all elements in the display at some stage of processing. In other words, the amount of dilution from a particular display item will depend on its location relative to the attentional focus, its grouping with other elements in the display, its features that match the expected features of the target, and other factors that affect attentional allocation. Another option to account for these data is to modify the perceptual load account to include a detailed description of how the different non-targets in the display interact to affect one another's processing. As Yeh and Lin have suggested, it may be possible to construct an account somewhere in between the pure perceptual load theory and the pure dilution theory that can explain all of these different experimental results, but it is likely to include a combination of factors that make it more complex than either of those original theories.

While Experiments 2 and 4 show that dilution is affected by the attentional focus, Experiment 3 demonstrates another informative aspect about dilution: that it occurs not because the basic features of the non-targets interfere with processing the features of the distractor, but because the non-target are activating letter representations that compete with the representation for the distractor letter. When the non-targets are inverted so that they do not match any letter representation, the competition is eliminated. The interference that underlies these effects appears to arise at the level of letter representations, and not lower down at the level of simple features.

These results give us a clearer view of how dilution occurs in the processing of multi-element displays, and how it can be prevented. As shown by Tsal and Benoni (2010) and by Wilson et al. (2011), items can contribute to dilution even when their location makes it clear that they are irrelevant to the task, but only if a sudden increment in luminance draws a certain amount of attention to them. Furthermore, the effects of a letter will only be diluted by other letters in the display, and not by items sharing basic features with the letters. Thus, dilution is not as widespread or as uniform as previous accounts predict. These results, like those of Yeh and Lin (2013), suggest that within multi-element displays, there is a complex interaction between the separate elements as they all compete for some level of attention, and that the allocation of attention is shaped by multiple factors working simultaneously.

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REFERENCES

Baylis, G. C., and Driver, J. (1992). Visual parsing and response competition. *Percept. Psychophys.* 51, 145–162. doi: 10.3758/BF03212239

Belopolsky, A. V., and Theeuwes, J. (2010). No capture outside the attentional window. *Vision Res.* 50, 2543–2550. doi: 10.1016/j.visres.2010.08.023

Belopolsky, A. V., Zwaan, L., Theeuwes, J., and Kramer, A. F. (2007). The size of an attentional window modulates attentional capture by color singleton. *Psychon. Bull. Rev.* 14, 934–938. doi: 10.3758/BF03194124

Benoni, H., and Tsal, Y. (2010). Where have we gone wrong? Perceptual load does not affect selective attention. *Vision Res.* 50, 1292–1298. doi: 10.1016/j.visres.2010.04.018

Biggs, A., and Gibson, B. S. (2010). Competition between color salience and perceptual load during visual selection can be biased by top-down set. *Atten. Percept. Psychophys.* 72, 53–64. doi: 10.3758/APP.72.1.53

Brown, T. L., Roos-Gilbert, L., and Carr, T. H. (1995). Automaticity and word perception: evidence form Stroop and Stroop dilution effects. *J. Exp. Psychol. Learn. Mem. Cogn.* 21, 1395–1411. doi: 10.1037/0278-7393.21.6.1395

Cave, K. R., Bush, W. S., and Taylor, T. G. (2010). Split attention as part of a flexible attentional system for complex scenes: comment on Jans, Peters, and De Weerd (2010). *Psychol. Rev.* 117, 685–696. doi: 10.1037/a0019083

Chen, Z. (2003). Attentional focus, processing load, and Stroop interference. *Percept. Psychophys.* 65, 888–900. doi: 10.3758/BF03194822

Chen, Z., and Cave, K. R. (2006). Reinstating object-based attention under positional certainty: the importance of subjective parsing. *Percept. Psychophys.* 68, 992–1003. doi: 10.3758/BF03193360

Cosman, J. D., and Vecera, S. P. (2012). Object-based attention overrides perceptual load to modulate visual distraction. *J. Exp. Psychol. Hum. Percept. Perform.* 38, 576–579. doi: 10.1037/a0027406

Duncan, J., and Humphreys, G. (1989). Visual search and stimulus similarity. *Psychol. Rev.* 96, 433–458. doi: 10.1037/0033-295X.96.3.433

Duncan, J., and Humphreys, G. (1992). Beyond the search surface: visual seach and attentional engagement. *J. Exp. Psychol. Hum. Percept. Perform.* 18, 578–588. doi: 10.1037/0096-1523.18.2.578

Eltiti, S., Wallace, D., and Fox, E. (2005). Selective target processing: perceptual load or distractor salience? *Percept. Psychophys.* 67, 876–885. doi: 10.3758/BF03193540

Eriksen, B. A., and Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Percept. Psychophys.* 16, 143–149.

Eriksen, C. W., and Hoffman, J. E. (1973). The extent of processing of noise elements during selective encoding from visual display. *Percept. Psychophys.* 14, 155–160.

Eriksen, C. W., and St. James, J. D. (1986). Visual attention within and around the field of focal attention: a zoom lens model. *Percept. Psychophys.* 40, 225–240.

Gatti, S. V., and Egeth, H. E. (1978). Failure of spatial selectivity in vision. *Bull. Psychon. Soc.* 11, 181–184.

Harms, L., and Bundesen, C. (1983). Color segregation and selective attention in a nonsearch target. *Percept. Psychophys.* 33, 11–19.

Hoffman, J. E. (1979). A two-stage model of visual search. *Percept. Psychophys.* 25, 319–327.

Jans, B., Peters, J. C., and de Weerd, P. (2010). Visual spatial attention to multiple locations at once: the jury is still out. *Psychol. Rev.* 117, 637–684. doi: 10.1037/a0019082

Johnson, D. N., McGrath, A., and McNeil, C. (2002). Cuing interacts with perceptual load in visual search. *Psychol. Sci.* 13, 284–287. doi: 10.1111/1467-9280.00452

Kahneman, D., and Chajczyk, D. (1983). Tests of the automaticity of reading: dilution of Stroop effects by color-irrelevant stimuli. *J. Exp. Psychol. Hum. Percept. Perform.* 9, 497–509.

Kramer, A. F., and Jacobson, A. (1991). Perceptual organization and focused attention: the role of objects and proximity in visual processing. *Percept. Psychophys.* 50, 267–284.

LaBerge, D., Brown, V., Carter, M., Bash, D., and Hartley, A. (1991). Reducing the effects of adjacent distractors by narrowing attention. *J. Exp. Psychol. Hum. Percept. Perform.* 17, 65–76. doi: 10.1037/0096-1523.17.1.65

Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. *J. Exp. Psychol. Hum. Percept. Perform.* 21, 451–468. doi: 10.1037/0096-1523.21.3.451

Lavie, N. (2005). Distracted and confused? Selective attention under load. *Trends Cogn. Sci.* 9, 75–82. doi: 10.1016/j.tics.2004.12.004

Lavie, N., and Cox, S. (1997). On the efficiency of visual selective attention: efficient visual search leads to inefficient distractor rejection. *Psychol. Sci.* 8, 395–398. doi: 10.1162/089892901753165791

Lavie, N., and De Fockert, J. W. (2003). Contrasting effects of sensory limits and capacity limits in visual selective attention. *Percept. Psychophys.* 65, 202–212. doi: 10.3758/BF03194795

Lavie, N., and Fox, E. (2000). The role of perceptual load in negative priming. *J. Exp. Psychol. Hum. Percept. Perform.* 26, 1038–1052. doi: 10.1037/0096-1523.26.3.1038

Lavie, N., and Tsal, Y. (1994). Perceptual load as a major determinant of the locus of selection in visual attention. *Percept. Psychophys.* 56, 183–197.

Marciano, H., and Yeshurun, Y. (2011). The effects of perceptual load in central and peripheral regions of the visual field. *Vis. Cogn.* 19, 367–391. doi: 10.1080/13506285.2010.537711

Miller, J. (1987). Priming is not necessary for selective-attention failures: semantic effects of unattended, unprimed letters. *Percept. Psychophys.* 41, 419–434.

Miller, J. (1991). The flanker compatibility effect as a function of visual angle, attentional focus, visual transients, and perceptual load: a search for boundary condition. *Percept. Psychophys.* 49, 270–288.

Murray, J. E., and Jones, C. (2002). Attention to local form information can prevent access to semantic information. *Q. J. Exp. Psychol. A* 55, 609–625. doi: 10.1080/02724980143000370

Neisser, U. (1967). *Cognitive Psychology.* Englewood Cliffs, NJ: Prentice Hall.

Paquet, L., and Craig, G. L. (1997). Evidence for selective target processing with a low perceptual load flankers task. *Mem. Cogn.* 25, 182–189.

Paquet, L., and Lortie, C. (1990). Evidence for early selection: precuing target location reduces interference from same-category distractors. *Percept. Psychophys.* 48, 382–388.

Schneider, W., Eschman, A., and Zuccolotto, A. (2002). *E-Prime User's Guide.* Pittsburgh, PA: Psychology Software Tools, Inc.

Theeuwes, J., Kramer, A. F., and Belopolsky, A. V. (2004). Attentional set interacts with perceptual load in visual search. *Psychon. Bull. Rev.* 11, 697–702. doi: 10.3758/BF03196622

Treisman, A. M. (1964). Selective attention in man. *Br. Med. Bull.* 20, 12–16.

Tsal, Y., and Benoni, H. (2010). Diluting the burden of load: perceptual load effects are simply dilution effects. *J. Exp. Psychol. Hum. Percept. Perform.* 36, 1645–1656. doi: 10.1037/a0018172

Wilson, D. E., Muroi, M., and MacLeod, C. M. (2011). Dilution, not load, affects distractor processing. *J. Exp. Psychol. Hum. Percept. Perform.* 37, 319–335. doi: 10.1037/a0021433

Yantis, S., and Johnston, J. C. (1990). On the locus of visual selection: evidence from focused attention tasks. *J. Exp. Psychol. Hum. Percept. Perform.* 16, 135–149. doi: 10.1037/0096-1523.16.1.135

Yantis, S., and Jonides, J. (1984). Abrupt visual onsets and selective attention: evidence from visual search. *J. Exp. Psychol. Hum. Percept. Perform.* 10, 601–621.

Yantis, S., and Jonides, J. (1990). Abrupt visual onsets and selective attention: voluntary versus automatic allocation. *J. Exp. Psychol. Hum. Percept. Perform.* 16, 121–134. doi: 10.1037/0096-1523.16.1.121

Yeh, Y.-Y., and Lin, S.-H. (2013). Two mechanisms of distractor dilution: visual selection in a continuous flow. *J. Exp. Psychol. Hum. Percept. Perform.* 39, 872–892. doi: 10.1037/a0030486

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Perceptual load and early selection: an effect of attentional engagement?

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The selection of task-relevant information from amongst task-irrelevant or distracting information is key to successful performance, and much debate has focused on the processing stage(s) at which this selection takes place. Early-selection theory claimed that the selection of task-relevant information occurs at an early perceptual level of processing, so that only targets are perceptually encoded (Cherry, 1953; Broadbent, 1958). In contrast, late-selection theory claimed that both targets and distractors are perceptually encoded and that target selection occurs at a late post-perceptual level of processing (DeutSch and DeutSch, 1963). Lavie (1995) attempted to reconcile these theories by suggesting that early and late selection occur, respectively, when the perceptual load associated with the selection of the target is high and low.

Thus, according to load theory, when the perceptual load associated with target selection is high, perceptual resources are completely exhausted with perceptual processing of the target and unavailable for perceptual processing of distractors; conversely, when the perceptual load associated with target selection is low, perceptual resources are not completely occupied with perceptual processing of the target and automatically spill over to allow perceptual processing of distractors. In sum, load theory suggests that early selection is possible only when perceptual capacity is exhausted. When capacity is not exhausted, post-perceptual mechanisms must be invoked to inhibit irrelevant information that received perceptual processing (Macdonald and Lavie, 2008).

The majority of studies providing evidence in support of load theory have used the flanker paradigm which presents distractors and targets at fixed separations (Eriksen and Eriksen, 1974) and have shown that higher perceptual load generates lower distractor interference. These studies interpret lower distractor interference under high perceptual load as an expression of spatial attention that is more narrowly focused on the target. In order to test this interpretation directly, we presented distractors at varying separations from targets in a variant of the flanker paradigm (Eriksen and St. James, 1986) and measured distractor interference as a function of separation to index the spatial profile of attention. In addition, and following Lavie (1995), we manipulated perceptual load using not just the more standard stimulus-based manipulations (involving varying the number of filler items surrounding the to-be-identified target item) but also task-based manipulations (involving varying the spatial-resolution difficulty of a secondary perceptual task performed after target identification). Note that stimulus-based manipulations are possibly confounded with "dilution" of distractors (Tsal and Benoni, 2010). For both types of perceptual load manipulations, however, we showed that the spatial profile of attention was more focused when perceptual load was high and less focused when it was low (Caparos and Linnell, 2009, 2010; Linnell and Caparos, 2011), consistent with the central tenet of load theory that perceptual load affects early perceptual-level selection.

Critically, however, high perceptual load only focused spatial attention when working memory load was low (i.e., when one, as opposed to six, digits were held in memory) and, thus, when cognitive resources were available (Linnell and Caparos, 2011). This finding is not consistent with the claim of load theory that high perceptual load focuses spatial attention automatically (and with the finding of Lavie et al., 2004, that perceptual and working memory load exert independent effects on distractor interference; see discussion of this finding in Caparos and Linnell, 2010, and in Linnell and Caparos, 2011). The fact that perceptual load only focuses spatial attention when cognitive resources are available raises the possibility that perceptual load is important in early selection not because it exhausts perceptual resources but rather because it engages cognitive resources sufficiently on the task in hand to focus spatial attention.

The requirement for cognitive resources may not be great since even groups that demonstrate impairments in cognitive control such as the elderly and high-trait-anxious can show levels of selection indistinguishable from their younger and low-trait-anxious counterparts under high perceptual load (Maylor and Lavie, 1998; Bishop, 2009). We argue that increasing perceptual load increases task difficulty in a straightforward fashion that only impacts perceptual difficulty; this does not challenge cognitive resources but simply engages them in the focusing of spatial attention (see also the suggestion of Eysenck and Derakshan, 2011, that "when the task is demanding and there are clear task goals, high-anxious individuals have a high level of motivation [and make] extensive use of attentional control strategies"). A high-perceptual-load task is according to this conception a task that perceptually draws one in; it encourages the investment of cognitive resources - that might otherwise have been spent on mind wandering or other distractions - on the focusing of spatial attention. Compatible with this, perceptual load has been reported to decrease self-reported mind-wandering and to improve selection in proportion to improvements in mind-wandering (Forster and Lavie, 2009).

In essence, we are arguing that perceptual load—whether it is manipulated using stimulus or task complexity—is a perceptual-difficulty manipulation that motivates cognitive engagement with a task. This is compatible with the common finding that perceptual load exerts considerably larger or more consistent effects on selection when it is blocked rather than varied from trial to trial (e.g., Theeuwes et al., 2004) but can also explain the smaller residual effects of load on a trial-by-trial basis. Although increasing perceptual load will increase perceptual difficulty, what is difficult and engaging to one individual or group of participants may not be difficult and engaging to another. Computer gamers and ASD participants have both been argued to possess more perceptual resources than controls and their greater distractibility at lower perceptual loads (Green and Bavelier, 2003; Remington et al., 2009) may be explained by these loads not being sufficiently perceptually difficult to induce cognitive engagement. This is a different account from that offered by load theory which does not invoke any differences in cognitive engagement; according to load theory, the key difference between groups that differ in their perceptual capacity is whether or not fixed-capacity perceptual resources are exhausted (Maylor and Lavie, 1998).

As soon as one explains the effect of perceptual load on early perceptual-level selection as an effect of attentional engagement one should allow that conditions of high perceptual load may not be the only ones supporting early selection; even when the perceptual difficulty of the task is low, early selection may be possible and distractors may not be perceptually processed. This is exactly what was found in a task of local selection where we showed that increasing task interest by increasing social relevance, without changing perceptual load, focused spatial attention and thus improved early perceptual-level selection (Linnell et al., 2013). In addition, groups that differ in their emotional responses and default attentional state also differ in their propensity for early perceptual-level selection: in a task of local selection with no emotional content, high-trait-anxious participants displayed more focused spatial attention than low-trait-anxious ones (Caparos and Linnell, 2012). High-trait-anxious individuals are likely to make more effort in order to avoid failure at a task (Staal, 2004; Sarter et al., 2006), resulting in cognitive resources being more engaged to focus spatial attention.

Differences in default attentional state may also underpin the far greater facility for early selection in remote peoples compared to urbanized peoples. The Himba are a remote people living in the savannah of northern Namibia; in a range of tasks of local selection, they consistently displayed more focused spatial attention than British participants living in London and than Himba who had adopted an urbanized way of life (Linnell et al., 2013). This was not a result of the Himba having fewer perceptual resources because they showed the same sensitivity to increasing perceptual load as British participants and showed focused spatial attention even at the lowest perceptual load (De Fockert et al., 2011). Rather, we argue that remote peoples have a default attentional state that favors full cognitive engagement with the task in hand, whereas urbanized peoples—perhaps because they are more stressed—have a default attentional state that favors the division of cognitive resources between monitoring the wider environment for dangers or opportunities and performing the task in hand (Linnell et al., 2013).

Our explanation of these default differences between urbanized and non-urbanized groups invokes a variant of the Yerkes-Dodson law (Yerkes and Dodson, 1908) that links task performance to attentional state by an inverted U-shaped function. According to this law, task performance—here attentional selection—peaks at an intermediate attentional state. This intermediate state may not be the default attentional state, at least in the urbanized peoples who have participated in most studies of attention. The default attentional state in urbanized peoples may favor late over early selection; processing contextual information at least to perceptual levels may be advisable in complex and dynamic urban environments—where distractors can suddenly become targets—and therefore worth the cost when distractors have to be ignored at post-perceptual levels in the service of task goals. Nevertheless, we are just starting to understand how altering the motivational significance of the task in hand may shift this balance (e.g., Padmala and Pessoa, 2011).

In sum, we suggest that altering the perceptual load associated with target processing—whether by stimulus-based or task-based manipulations—is just one of a number of ways of affecting the engagement of cognitive resources with the task in hand and that it is increasing engagement with a target stimulus that is key to achieving its early perceptual-level selection and not the exhausting of perceptual capacity. Attentional engagement and early perceptual selection (i) may be the default in remote peoples even when perceptual load is low and there are no special motivating factors and (ii) may be demonstrable in urbanized peoples when they are confronted not just with high perceptual load but also with tasks of social or emotional significance. It is time not just to bring the study of attention and motivation together, but to recognize that motivation is key to a core construct of attention research, namely perceptual load.

REFERENCES

Bishop, S. J. (2009). Trait anxiety and impoverished prefrontal control of attention. *Nat. Neurosci.* 12, 92–98. doi: 10.1038/nn.2242

Broadbent, D. E. (1958). *Perception and Communication*. New York, NY: Pergamon Press. doi: 10.1037/10037-000

Caparos, S., and Linnell, K. J. (2009). The interacting effect of load and space on visual selective attention. *Vis. Cogn.* 17, 1218–1227. doi: 10.1080/13506280902924083

Caparos, S., and Linnell, K. J. (2010). The spatial focus of attention is controlled at perceptual and cognitive levels. *J. Exp. Psychol. Hum. Percept. Perform.* 36, 1080–1107. doi: 10.1037/a0020367

Caparos, S., and Linnell, K. J. (2012). Trait anxiety focuses spatial attention. *Emotion* 12, 8–12. doi: 10.1037/a0026310

Cherry, E. C. (1953). Some experiments on the recognition of speech with one and with two ears. *J. Acoust. Soc. Am.* 25, 975–979. doi: 10.1121/1.1907229

De Fockert, J., Caparos, S., Linnell, K. J., and Davidoff, J. (2011). Reduced distractibility in a remote culture. *PLoS ONE* 6:e26337. doi: 10.1371/journal.pone.0026337

DeutSch, J. A., and DeutSch, D. (1963). Attention: some theoretical considerations. *Psychol. Rev.* 70, 80–90. doi: 10.1037/h0039515

Eriksen, B. A., and Eriksen, C. W. (1974). Effects of noise letters upon identification of a target letter in a nonsearch task. *Percept. Psychophys.* 16, 143–149. doi: 10.3758/BF03203267

Eriksen, C. W., and St. James, J. D. (1986). Visual-attention within and around the field of focal attention - a zoom lens model. *Percept. Psychophys.* 40, 225–240. doi: 10.3758/BF03211502

Eysenck, M. W., and Derakshan, N. (2011). New perspectives in attentional control theory. *Pers. Individ. Dif.* 50, 955–960. doi: 10.1016/j.paid.2010.08.019

Forster, S., and Lavie, N. (2009). Harnessing the wandering mind: the role of perceptual load. *Cognition* 111, 345–355. doi: 10.1016/j.cognition.2009.02.006

Green, C., and Bavelier, D. (2003). Action video game modifies visual selective attention. *Nature* 423, 534–537. doi: 10.1038/nature01647

Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. *J. Exp. Psychol. Hum. Percept. Perform.* 21, 451–468. doi: 10.1037/0096-1523.21.3.451

Lavie, N., Hirst, A., de Fockert, J. W., and Viding, E. (2004). Load theory of selective attention and cognitive control. *J. Exp. Psychol. Gen.* 133, 339–354. doi: 10.1037/0096-3445.133.3.339

Linnell, K. J., and Caparos, S. (2011). Perceptual and cognitive load interact to control the spatial focus of attention. *J. Exp. Psychol. Hum. Percept. Perform.* 37, 1643–1648. doi: 10.1037/a0024669

Linnell, K. J., Caparos, S., De Fockert, J., and Davidoff, J. (2013). Urbanisation decreases attentional engagement. *J. Exp. Psychol. Hum. Percept. Perform.* doi: 10.1037/a0031139. [Epub ahead of print].

Macdonald, J. S., and Lavie, N. (2008). Load induced blindness. *J. Exp. Psychol. Hum. Percept. Perform.* 34, 1078–1091. doi: 10.1037/0096-1523.34.5.1078

Maylor, E. A., and Lavie, N. (1998). The influence of perceptual load on age differences in selective attention. *Psychol. Aging* 13, 563–573. doi: 10.1037/0882-7974.13.4.563

Padmala, S., and Pessoa, L. (2011). Reward reduces conflict by enhancing attentional control and biasing visual cortical processing. *J. Cogn. Neurosci.* 23, 3419–3432. doi: 10.1162/jocn_a_00011

Remington, A., Swettenham, J., Campbell, R., and Coleman, M. (2009). Selective attention and perceptual load in autism spectrum disorder. *Psychol. Sci.* 20, 1388–1393. doi: 10.1111/j.1467-9280.2009.02454.x

Sarter, M., Gehring, W. J., and Kozak, R. (2006). More attention must be paid: the neurobiology of attentional effort. *Brain Res. Rev.* 51, 145–160. doi: 10.1016/j.brainresrev.2005.11.002

Staal, M. A. (2004). *Stress, Cognition, and Human Performance: A Literature Review and Conceptual Framework.* Hanover, MD: National Aeoronautics and Space Administration.

Theeuwes, J., Kramer, A. F., and Belopolsky, A. V. (2004). Attentional set interacts with perceptual load in visual search. *Psychon. Bull. Rev.* 11, 697–702. doi: 10.3758/BF03196622

Tsal, Y., and Benoni, H. (2010). Diluting the burden of load: perceptual load effects are simply dilution effects. *J. Exp. Psychol. Hum. Percept. Perform.* 36, 1645–1656. doi: 10.1037/a0018172

Yerkes, R. M., and Dodson, J. D. (1908). The relation of strength of stimulus to rapidity of habit-formation. *J. Comp. Neurol. Psychol.* 18, 459–482. doi: 10.1002/cne.920180503

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Learning to ignore salient color distractors during serial search: evidence for experience-dependent attention allocation strategies

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Previous research has investigated whether visual salience (i.e., how much an item stands out) or perceptual load (i.e., display complexity) is the dominant factor in visual selective attention. The evidence has been mixed, with some findings supporting a dominant role for visual salience and some findings supporting a dominant role for perceptual load. However, the complex displays used to impose high perceptual load also introduce a third factor that has gone understudied until recently: the interplay between identity dilution and exposure duration. Adding display items to increase perceptual load dilutes a distractor's identity, which could decrease interference, but the task generally takes longer, which could increase distractor interference. To clarify how these factors interact, the present study used converging measures of distractor interference—both compatibility and singleton presence—to disambiguate effects due to salience, perceptual load, and identity dilution/exposure duration. Compatibility effects support perceptual load as the dominant factor, whereas singleton presence effects do not (Experiment 1). Consistent with salience-based mechanisms, significant distractor processing (both compatibility and presence effects) occurred under high perceptual load when singleton present trials preceded singleton absent trials (Experiment 2A). However, consistent with load-based mechanisms, non-significant compatibility effects occurred under high perceptual load when singleton absent trials preceded singleton present trials (Experiment 2B). Thus, the competition between salience-based and load-based mechanisms depended on the amount of prior experience with singleton present vs. absent displays, which in turn depended on the use of broad vs. narrow attentional allocation strategies. These experience-dependent effects provide further evidence that attention allocation strategies are contingent on factors such as task context and experience.

Keywords: salience, visual selection, visual attention, dilution, perceptual load

Visual selective attention enables observers to focus on goal-relevant information in the presence of irrelevant information. Currently, perceptual load theory (Lavie, 1995) is the leading view of visual selection, but this perspective has come under attack from a number of different sources. Two alternative accounts suggest that visual salience (e.g., Eltiti et al., 2005) or distractor dilution (e.g., Tsal and Benoni, 2010) describe visual selection better than perceptual load. However, distinguishing between these issues is often complicated as they tend to be manipulated through similar means, such as how adding heterogeneous letters to increase display size both reduces form-related salience and dilutes the critical distractor (Biggs and Gibson, in press). The present study will disambiguate these theoretical interpretations by providing multiple measures: singleton distractor presence effects will better correspond to salience, and singleton distractor compatibility effects will better correspond to dilution. Furthermore, we can explore how these bottom-up factors of salience and dilution interact with the top-down experience of the observer. In so doing, the present experiments will clarify the theoretical interpretation obtained from different patterns of distractor interference, and allow us to confidently advance our understanding of the factors that influence the efficiency of visual selective attention.

According to the *perceptual load account* of visual selection (Lavie and Tsal, 1994; Lavie, 1995, 2005, 2006; Lavie and Cox, 1997; Lavie et al., 2004), the ability to ignore distractors depends critically on what perceptual load the display imposes on an observer. This is because the extent to which critical distractors are processed depends on the extent to which perceptual capacity is consumed by the set of relevant items (i.e., potential target and non-target items). When the display is relatively small, relevant information does not consume all available resources and perceptual resources spill over to the distractor, typically resulting in significant distractor processing, or late selection. When the number of relevant items is relatively large, perceptual resources do not spill over to the distractor because they are fully consumed in processing the relevant items, typically resulting in non-significant distractor interference, or early selection. This idea remains the predominant view of visual selection as it appears to settle the long standing debate of early vs. late selection (Broadbent, 1958;

Deutsch and Deutsch, 1963) by suggesting that the locus of selection is not fixed.

However, recent evidence has suggested that perceptual load theory may not be as comprehensive in explaining visual selection as once believed. Such evidence has tended to come in one of two forms. The first is in disrupting the empirical hallmark of perceptual load, where significant distractor interference occurs under low load and is eliminated or reduced under high load. Some evidence has challenged load theory by showing non-significant interference under low load (e.g., Paquet and Craig, 1997) or significant interference under high load (e.g., Biggs and Gibson, 2010; Cosman and Vecera, 2010). The second means of challenging load theory is through an alternative explanation as to why the empirical pattern arises in the first place (e.g., Tsal and Benoni, 2010). In either case of disputing evidence, other factors were shown to influence visual selection above and beyond the account of perceptual load theory. Two of these factors, particularly as the visual display is concerned, are salience and dilution.

According to the *visual salience account* of visual selection (Theeuwes, 1991, 1992, 1994; Theeuwes and Burger, 1998; Eltiti et al., 2005) the ability to ignore distractors depends critically on the relative salience of the distractor in question. This is supposedly because focal attention can be captured in a reflexive fashion by salient objects and events in the world. In this view, significant distractor interference should be observed regardless of the number of relevant items because the salience of a uniquely-colored distractor remains high across any load manipulation. Previous studies have placed load and salience in direct competition to better understand the relative contributions of each factor to visual selection, but the results have been mixed (Gibson and Bryant, 2008; Biggs and Gibson, 2010). On the one hand, some evidence suggests that load can dominate salience when low and high load displays are presented randomly, as reflected by a significant decrease in distractor interference for high load vs. low load trials (Gibson and Bryant, 2008; Biggs and Gibson, 2010, Experiment 1). On the other hand, some evidence suggests that salience can dominate load when low and high load displays are presented in separate blocks, as reflected by equal amounts of distractor interference observed across display load (Biggs and Gibson, 2010, Experiment 2).

The latter results, suggesting that salience can dominate load when knowledge of load increases (i.e., when high- and low-load displays are presented in separate blocks of trials), appear inconsistent with findings that salience effects typically decrease as display knowledge increases (Lamy and Yashar, 2008; Müller et al., 2009; but see, Pinto et al., 2005). Although, the fact that visual salience has any effect at all during the performance of this serial search task might be considered surprising. This is because observers typically adopt a relatively narrow focus of attention during these tasks and the computation of visual salience is thought to require a relatively wide focus of attention (Belopolsky et al., 2007). Because this pattern of distractor interference appears to lead to a puzzling conclusion, it is possible that the distractor interference observed by Biggs and Gibson (2010, Experiment 2) does not reflect capture by salience, but rather the operation of some other mechanism.

Another such mechanism affecting these various results is the dilution of distractor interference (Benoni and Tsal, 2010; Tsal and Benoni, 2010; Wilson et al., 2011). According to this alternative dilution account, there are two opposing factors that may be confounded with manipulations of load. One factor involves the dilution of distractor identities by other display items (see also Benoni and Tsal, 2010; Wilson et al., 2011). For example, a common manipulation of perceptual load is display size (e.g., Lavie, 1995; Lavie and Cox, 1997), but the addition of multiple non-target identities decreases (or "dilutes") the amount of interference the distractor identity is capable of generating. High perceptual load then produces less distractor interference due to the potency of the critical distractor, not a difference in visual selection. The second factor involves exposure duration. When exposure duration is not controlled, it usually increases as a function of perceptual load because task performance is more difficult under conditions of high load than under conditions of low load. Increases in exposure duration, in turn, typically cause increases in distractor interference because observers are exposed to the distractors for longer periods of time (Gibson et al., 2009).

The magnitude of distractor interference observed in a given condition may reflect a combination of the offsetting effects through both dilution and exposure duration. In particular, when load is low, there is relatively weak dilution of the distractor's identity (which should result in increased distractor interference), but exposure duration is relatively short (which should result in decreased distractor interference). In contrast, when load is high, there is relatively strong dilution of the distractor's identity (which should result in decreased distractor interference), but exposure duration is relatively long (which should result in increased distractor interference). Thus, Biggs and Gibson (2010, Experiment 2) may have observed equal amounts of distractor interference across their manipulation of load not because the salient distractor consistently captured focal attention, but rather because the shifting balance between dilution and exposure duration that occurred with a change in perceptual load resulted in a constant amount of distractor processing.

If this alternative account of Biggs and Gibson's (2010, Experiment 2) findings is plausible, then visual salience may actually have little effect on visual selection in this paradigm. However, a primary issue is that these results rely upon an empirical pattern of distractor interference obtained from distractor compatibility effects, which potentially have multiple explanations. For example, non-significant distractor compatibility effects under high perceptual load could mean a lack of perceptual resources for processing, a non-salient distractor incapable of attracting sufficient resources to induce processing, or substantial distractor dilution. Another source of evidence is required to help delineate some of these possibilities.

This converging evidence can be provided by using different methods to measure distractor interference—singleton distractor presence and singleton distractor compatibility. In the present study, singleton distractor presence will be manipulated by whether a singleton distractor ring is present or absent from the display, whereas singleton distractor compatibility will be manipulated by altering the identity of a singleton distractor to be incompatible, neutral, or compatible with the target letter. These different manipulations provide two advantages to the present study. The first is that they easily map onto the factors of salience and dilution. Salience can correspond to the presence (or absence) or a color singleton distractor, and interference can be measured by the difference between response times when the distractor is present vs. when it is absent. Dilution can correspond to the potential conflict between target and distractor identities, which can be measured by the difference in response times when an incompatible vs. neutral distractor is present. Moreover, using a color singleton distractor allows it to remain salient whenever present, which circumvents an issue with distractor dilution. For example, if display size is the only manipulation in a letter search, then the increase in non-target letters to increase display size both dilutes the distractor and reduces its salience. The Gibson and Bryant (2008) paradigm allows us to include both salience and dilution manipulations because it includes a color singleton distractor, which can be made present or absent, and a letter appears inside the color singleton ring, which can be made incompatible, neutral, or compatible with the target identity. Our critical distractor can thus remain equally salient under both low and high perceptual load despite the introduction of additional non-target letter identities. Another advantage is that these different measures of distractor interference provide different insights into cognitive processing. Singleton distractor presence can measure the extent to which a particular item impacts attention, whereas singleton distractor compatibility effects can measure the extent to which the same item is processed. Thus, if any particular factor (e.g., perceptual load, visual salience, distractor dilution) is capable of fully explaining visual selection, its effects should be revealed across multiple measures.

EXPERIMENT 1

Studies using the additional singleton paradigm (e.g., Theeuwes, 1991, 1992) have routinely manipulated the presence vs. absence of a salient distractor to measure attentional capture. In these studies, observers searched for a form singleton while also attempting to ignore an irrelevant color singleton. The critical results showed that RTs were significantly slower when the color singleton was present in the display relative to when it was absent. These results were interpreted as follows: in the distractor absent condition, observers searched for the form singleton, which they were able to detect efficiently regardless of display load. However, although observers also detected the form singleton efficiently regardless of display load in the distractor present condition, they were overall slower because attention was first shifted to the more salient color singleton before it was redirected to the relevant form singleton, thus causing a constant increase in search time. Furthermore, manipulations of distractor compatibility have also provided evidence for the notion that focal attention is shifted to the location of the irrelevant color singleton because significant distractor compatibility effects are typically observed in the additional singleton paradigm as well (Theeuwes et al., 2000). In short, manipulations of both singleton distractor presence and singleton distractor compatibility can lead to complementary findings within the context of the additional singleton paradigm, with the former manipulation typically resulting in a search-time cost and the latter manipulation typically resulting in interference due to the distractor identity.

Inclusion of a singleton distractor presence manipulation in the serial search paradigm used by Gibson and Bryant (2008; also Biggs and Gibson, 2010), in addition to the distractor compatibility manipulation, has the potential to provide converging evidence for any conclusion seeking to explain differences in distractor interference under varying conditions of perceptual load. Accordingly, our experimental manipulations include both singleton distractor presence and distractor compatibility under conditions of both low and high perceptual load. Note that consistent with Biggs and Gibson's Experiment 2, observers had full knowledge of perceptual load in the present experiment by virtue of the fact that low and high load displays were presented in separate blocks.

If the pattern of distractor interference observed in the low and high load conditions of Biggs and Gibson's Experiment 2 resulted from attentional capture, then singleton distractor presence should have some effect on the dynamics of visual search. In particular, based on previous evidence (Theeuwes, 1991, 1992), there is reason to expect that singleton distractor presence should result in a search-time cost and the distractor compatibility manipulation should continue to result in distractor interference because attention is routinely shifted to the salient color distractor first. In contrast, we can assess exposure to the singleton distractor and dilution through a comparison between the singleton distractor presence and compatibility manipulations. The role of exposure to the distractor can be assessed by singleton distractor presence, which should result in significant search time costs, but it can be dissociated from dilution, which should result in non-significant distractor interference effects under high perceptual load as the additional non-target letters will dilute the distractor. If the presence of the singleton distractor has no effect and we only observe differences in distractor compatibility effects, then perceptual load theory offers the best explanation of the results.

METHOD

Participants

Twenty-three undergraduate students from the University of Notre Dame participated in the experiment for partial completion of a course requirement. Data from two observers were removed due to an error rate over 20%, and one for not complying with the instructions (i.e., continually responding as though the singleton distractor identity were the target letter). All observers reported normal or corrected-to-normal visual acuity without color deficits.

Stimuli and apparatus

The search displays were similar to those used by Biggs and Gibson (2010). The items appearing in the target display were placed at equal intervals on an imaginary circle with radius of 3.2° visual angle at a viewing distance of 57 cm. Each item was a letter subtending 0.76° in height and 0.55° in width surrounded by a ring with diameter of 1.4°. The rings were either green (18.81 cd/m^2) or red (18.81 cd/m^2), but the letters were always gray (18.48 cd/m^2). In the four-item displays, the items were placed at the four cardinal locations, and in the 12-item displays, two additional items were placed in between each of these cardinal locations. In the distractor absent condition, all the rings had the same color (red or green). In the distractor present condition, all but one of the rings had the same color; the remaining "singleton distractor ring" appeared in the opposite color. The commonly-colored rings always contained one of the two target letters (*E* or *R*) and a variable number of non-target letters (*H*, *P*, *N*, *K*, or *F*). When the singleton distractor ring was present, it contained a letter that was equally likely to be incompatible, neutral (*T*), or compatible with respect to the target's identity. When the singleton distractor was absent, the extra commonly-colored ring that replaced the singleton distractor ring always contained the letter *T* (as in the neutral condition). Responses were measured with a custom-made button box (Lafayette Instruments) and recorded to the nearest millisecond. Timing and presentation of stimuli were controlled by the DMDX experimental software program (Forster and Forster, 2003).

Procedure

See **Figure 1** for a sample trial sequence. A fixation dot appeared for 500 ms and was followed by the target display. Observers were instructed to keep their eyes on the fixation dot and search among the commonly-colored rings for the target while ignoring any uniquely-colored rings in the display. Observers were instructed to press the left key as quickly and as accurately as possible when they thought the target display contained the *R*, and they were instructed to press the right key as quickly and as accurately as possible when they thought the target display contained the *E*. The target display remained visible until response or until 4 s elapsed.

Observers had full knowledge of color conditions and perceptual load on any given trial in the present experiment. More specifically, each observer was exposed to only one of the two possible color assignments for the target/non-targets and distractor rings during the experimental session. For example, a given participant would see red target and non-target rings throughout the entire experiment with a green singleton distractor ring, whereas another participant would see the reverse assignment. The two color assignments were counterbalanced across observers. Upon answering, the computer proceeded automatically to the next experimental trial. Observers completed a practice block of 12 trials before each perceptual load condition. Half of the experimental trials were singleton distractor present trials, and half were singleton distractor absent trials; there were 864 total experimental trials. Order of load condition viewed first (low/high or high/low) was also counterbalanced across participants.

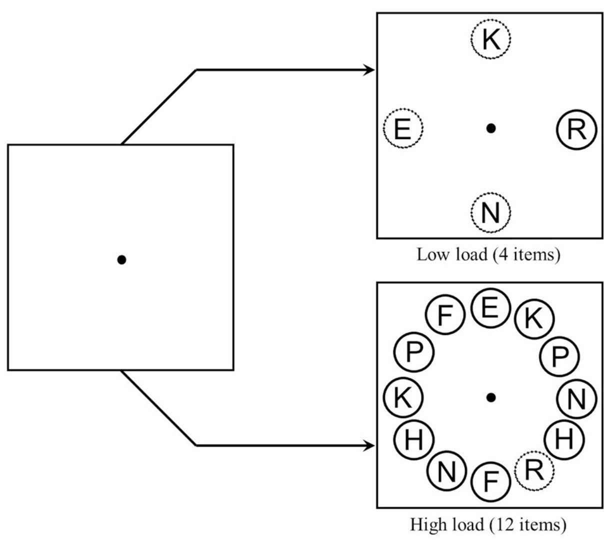

FIGURE 1 | Sample trial sequence. Each trial began with a fixation display for 500 ms, followed by the experimental display which remained on screen until a response was made. Solid lines represent green circles, and dotted lines represent red circles as used in the actual experiment.

RESULTS

Note that incorrect key responses, response latencies greater than 4000 ms (the time limit of the experiment), or response latencies less than 200 ms (considered anticipatory and not intentional responses to specific targets) were treated as errors and excluded from the RT analyses in this and all subsequent experiments reported with this study (note that less than 1% of the data were excluded based on the two response latency criteria). Analyses focused on two measures of distractor processing: singleton distractor compatibility and singleton distractor presence. The analysis of singleton distractor compatibility provided a measure of distractor processing (incompatible distractor condition [I] - neutral distractor condition [N]); and, the analysis of singleton distractor presence provided a measure of the cost of systematically attending to the singleton distractor (neutral distractor condition [N] - singleton distractor absent condition [A]). Because the same experimental data is examined through both singleton distractor compatibility and singleton distractor presence, we will correct for the multiple comparisons with a Bonferonni correction, making our critical p value for significance 0.025 ($\alpha/2$). Mean correct RTs are shown in **Figure 2** as a function of perceptual load and distractor condition. Corresponding error rates are listed in **Table 1**.

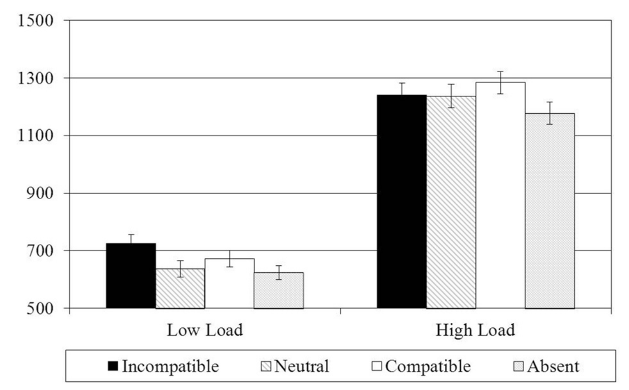

FIGURE 2 | Mean RTs (in ms) shown as a function perceptual load and distractor condition in Experiment 1. Error bars reflect the standard error of the mean.

Table 1 | Percent error rates listed as a function of perceptual load and distractor condition in Experiment 1.

	Distractor condition			
	Incompatible	**Neutral**	**Compatible**	**Absent**
Low load	7.30 (1.80)	3.48 (0.85)	3.55 (0.64)	3.02 (0.82)
High load	4.72 (0.84)	4.26 (0.73)	7.51 (1.38)	4.06 (0.72)

(Standard errors appear in parentheses).

Singleton distractor compatibility

A 2 × 2 within-subjects ANOVA was conducted on mean correct RTs with perceptual load (low load vs. high load) and singleton distractor compatibility (incompatible vs. neutral) as the two within-subjects variables. There was a significant main effect of perceptual load, $F_{(1,\ 19)} = 286.79$, $p < 0.001$, $\eta_p^2 = 0.94$, with faster RTs in the low load condition (680 ms) than in the high load condition (1238 ms); and, there was also a significant main effect of singleton distractor compatibility, $F_{(1,\ 19)} = 17.67$, $p < 0.001$, $\eta_p^2 = 0.48$, with RTs in the incompatible distractor condition (982 ms) being slower than RTs in the neutral distractor condition (937 ms). Most importantly, however, these results were qualified by a significant perceptual load × singleton distractor compatibility interaction, $F_{(1,\ 19)} = 12.17$, $p < 0.01$, $\eta_p^2 = 0.39$, which indicated a larger distractor compatibility effect in the low load condition [I – N = 87 ms, $t_{(19)} = 7.72$, $p < 0.001$] than in the high load condition [I – N = 3 ms, $p > 0.5$].

An identical within-subjects ANOVA was performed on error rates. There was a significant main effect of distractor compatibility, $F_{(1,\ 19)} = 7.77$, $p < 0.025$, $\eta_p^2 = 0.29$, with fewer errors committed in the neutral distractor condition (3.87%) than in the incompatible distractor condition (6.01%). The interaction between these two variables approached significance $F_{(1,\ 19)} = 3.66$, $p = 0.071$, $\eta_p^2 = 0.16$, indicating a larger singleton distractor compatibility effect in the low load condition [I – N = 3.82%, $t_{(19)} = 2.57$, $p < 0.025$] than in the high load condition [I – N = 0.47%, $p > 0.5$]. Hence, these findings do not compromise the RT findings reported above.

Singleton distractor presence

A 2 × 2 within-subjects ANOVA was conducted on mean correct RTs with perceptual load (low load vs. high load) and singleton distractor presence (present vs. absent) as the two within-subjects variables. There was significant main effect of perceptual load, $F_{(1,\ 19)} = 290.86$, $p < 0.001$, $\eta_p^2 = 0.94$, with faster RTs in the low load condition (631 ms) than in the high load condition (1207 ms); and, there was also a marginally significant main effect of singleton distractor presence, $F_{(1,\ 19)} = 17.72$, $p < 0.001$, $\eta_p^2 = 0.48$, with RTs in the neutral distractor condition (937 ms) being slower than RTs in the singleton distractor absent condition (901 ms). Most importantly, however, these results were qualified by a significant perceptual load × singleton distractor presence interaction, $F_{(1,\ 19)} = 7.59$, $p < 0.025$, $\eta_p^2 = 0.29$, which indicated a smaller singleton distractor presence effect in the low load condition [N − A = 13 ms, $t_{(19)} = 1.53$, $p = 0.14$] than in the high load condition [N − A = 59 ms, $p < 0.001$]. An identical within-subjects ANOVA was performed on error rates. There were no significant main effects or a significant interaction in the error rates (all Fs < 1).

DISCUSSION

Based on singleton distractor compatibility effects, we observe the typical perceptual load results where significant interference under low perceptual load was eliminated under high perceptual load. The singleton distractor remained salient in both low and high load conditions, yet its identity does not seem to have been processed. This evidence appears to support a perceptual load account of distractor processing. However, we observed the reverse for singleton distractor presence effects as the interference was non-significant under low load and significant under high load. Salience could explain why the singleton distractor presence effects were stronger under high perceptual load if we assume that, since all items are processed under low perceptual load anyway, salience is a much more important issue for the limited processing available under high perceptual load. The more complex high load displays were also on-screen longer due to the more complicated search, which indicates a difference in the amount of exposure to the critical distractor. The idea of exposure to the distractor is an intriguing one, particularly if we expand the notion to consider exposure as the amount of exposure to singleton distractors across the entire experiment instead of exposure during an individual trial. Some evidence does suggest that distractor rejection can depend upon prior experience (Leber and Egeth, 2006a,b; Vatterott and Vecera, 2012), which would indicate that exposure is more important to consider across the experiment rather than during a single trial or only under high perceptual load.

To address this issue, we divided up the low and high load trials into four blocks each based upon when the observed encountered a given trial during the experiment (leaving over 100 trials occurring in each block for each perceptual load condition). The results are shown in **Figure 3**. Under low load, the division seems to support the observations made from overall singleton distractor presence and compatibility effects. Singleton distractor presence seems to make very little difference as the singleton distractor neutral and absent trials were almost identical across the entire experiment. However, under high perceptual load, interference caused by the presence of a singleton distractor varies significantly. Singleton distractor presence was significant in the first block [N − A = 129 ms, $t_{(19)} = 2.89$, $p < 0.01$] and approached significance in the third block [N − A = 74 ms, $t_{(19)} = 2.36$, $p < 0.05$], but was non-significant in the second block [N − A = −5 ms, $p > 0.50$] and fourth block [N − A = 48 ms, $t_{(19)} = 1.36$, $p = 0.19$]. The change in the presence effect from the first to second block is largely due to the dramatic drop in response times when the singleton distractor was present, but thereafter the incompatible distractor condition begins to plateau. Continued decline in the singleton distractor absent condition, and some variance in the distractor neutral condition, is responsible for the differences in the latter portion of the experiment.

The observer appears to adopt a strategy sufficient to overcome distractor processing (e.g., block 2) only to see its effects short-lived. So, the exposure or experience of the observer appears

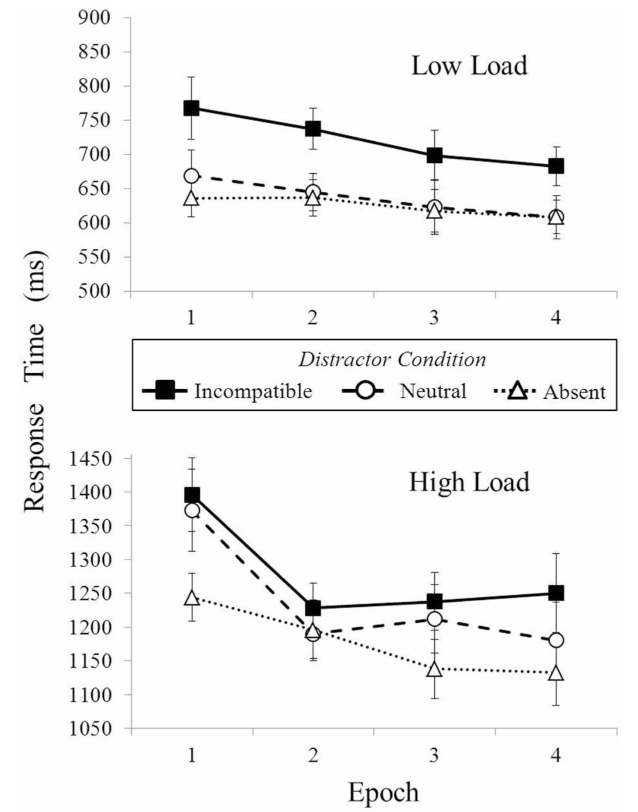

FIGURE 3 | Mean RTs (in ms) shown as a function perceptual load and distractor condition in Experiment 1. Epoch represents when during the experiment the trial occurred as divided into quarters. Error bars reflect the standard error of the mean.

to matter more under high load than low load, but it is difficult to make any specific argument for a learned strategy. Arguing for successful suppression of the distractor seems inappropriate given the variance in presence effects, yet with the singleton distractor appearing at random intervals, the only concrete conclusion is that exposure to the singleton distractor across the experiment impacts attention. A more controlled measure of singleton distractor presence is required to say more.

EXPERIMENT 2

Experiment 1 appears to better support a dilution account of visual selection rather than the alternative explanations of perceptual load and salience. More importantly, exposure to the distractor seems to be a highly influential aspect, especially when we consider exposure as an experiment-wide issue rather than a within-trial issue. This highlights the potential impact of experience-dependent aspects of attention, which alter how an individual processes the world based upon their previous interactions with specific stimuli. For example, distractor interference can vary as a function of individual exposure to the distractor, and whether that particular observer has been able to develop an effective distractor suppression strategy (Müller et al., 2009; Zehetleitner et al., 2012). These examples involve specific distractors that the observer learns to filter out, which saves people from random city sounds and annoying siblings; all possible through a learned process of sustained attentional suppression (Dixon et al., 2009; Kelley and Yantis, 2009).

These experience-dependent issues raise two relevant questions for the present investigation. First, are these mechanisms only important for high perceptual load where strategy and salience appear to have the largest impact? If so, then effective means of suppressing distractors under low perceptual load require some other means of directing attention, such as a valid spatial cue (Johnson et al., 2002). If not, then experience-dependent mechanisms are important for both low and high perceptual load. The second question involves why there is a change in distractor processing. Increased distractor processing appears to occur when the task context biases the observer toward processing the distractor (Biggs and Gibson, 2010), but experience-dependent mechanisms all appear to revolve around using distractors to either better filter information (Leber and Egeth, 2006a,b; Dixon et al., 2009; Vatterott and Vecera, 2012) or to use distractors to more effectively guide attention, as with contextual cuing (Chun and Jiang, 1998, 1999). Salient distractors appear to require more effort to successfully filter out from processing, which suggests that experience-dependent mechanisms are providing the observer with a more effective filter.

However, an alternative is that salient distractors are successfully ignored when the observer becomes better at allocating attention to relevant stimuli; this idea essentially says that the best way to truly ignore something is to focus on something else. Consider the attentional white bear phenomenon (Tsal and Makovski, 2006), where being told to ignore a distractor results in the observer allocating attention to it. Any effort to suppress something, even one which develops effectively over time, still requires an effort. So, the more effective method of ignoring distractors may simply be to pay them no attention whatsoever and prioritize attention only to the relevant stimuli.

Using the same paradigm as Experiment 1, we will test this possibility by blocking distractor presence rather than randomly presenting the distractor. If observers are developing better mechanisms of filtering the distractor, then blocked distractor presence should enhance their opportunity to develop and employ any such filter. The result would be decreased distractor interference through singleton distractor presence or singleton compatibility effects. However, if this ability depends upon more efficient allocation of attention only to relevant target information, then it will require practice with singleton distractor absent rather than singleton distractor present circumstances. This finding would be supported by a difference that depends on whether or not a block of singleton distractor absent trials preceded the singleton distractor present trials. Only when a block of singleton distractor absent trials appear first would the observer have the time to appropriately learn to attend to the relevant target information, which would allow them to ignore a salient distractor simply by attending to something else rather than putting effort into active suppression.

EXPERIMENT 2A

METHOD

Participants

Seventeen undergraduate students from the University of Notre Dame participated in the experiment for partial completion of a course requirement. All observers reported normal or corrected-to-normal visual acuity without color deficits.

Stimuli and apparatus

Identical to Experiment 1.

Procedure

Each observer was exposed to four separate blocks of trials in this experiment. Half of the observers saw this order: high load, distractor present; high load, distractor absent; low load, distractor present; low load, distractor absent. The other half of the observers saw this order: low load, distractor present; low load, distractor absent; high load, distractor present; high load, distractor absent. Note that blocks of distractor present trials always preceded blocks of distractor absent trials within each load condition in Experiment 2A (see Experiment 2B for additional manipulations). There were 216 experimental trials presented in each of the four blocks (864 total experimental trials) and a representative set of practice trials preceded each block. A different random order of experimental trials was presented to each observer within each block.

RESULTS

Mean correct RTs are shown in the top panel of **Figure 4** as a function of perceptual load and distractor condition. Corresponding error rates are listed in **Table 2**.

Singleton distractor compatibility

A 2 × 2 within-subjects ANOVA was conducted on mean correct RTs with perceptual load (low load vs. high load) and singleton distractor compatibility (incompatible vs. neutral) as the two within-subjects variables. As expected, there was a significant main effect of perceptual load, $F_{(1, 16)} = 201.31$, $p < 0.001$, $\eta_p^2 = 0.93$, with faster RTs in the low load condition (683 ms) than in the high load condition (1401 ms). Also as expected, there was a significant main effect of singleton distractor compatibility,

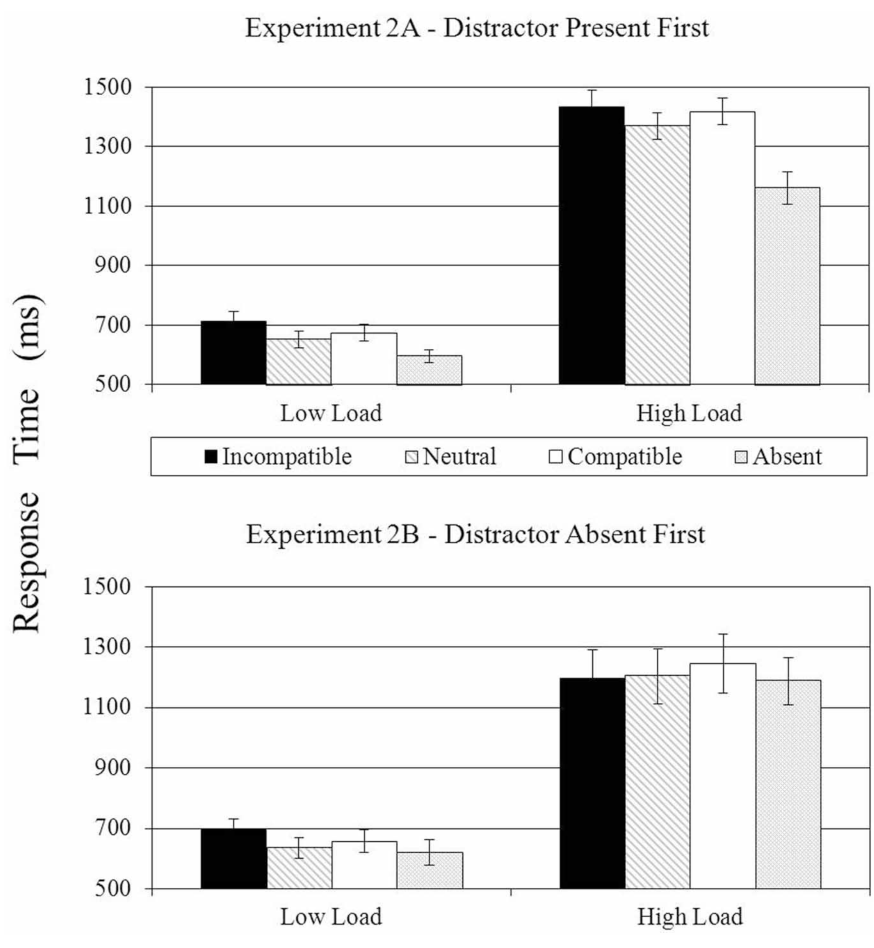

FIGURE 4 | Mean RTs (in ms) shown as a function perceptual load and distractor condition in Experiments 2A (top panel) and Experiment 2B (bottom panel). Error bars reflect the standard error of the mean.

Table 2 | Percent error rates listed as a function of perceptual load and distractor condition in Experiments 2A and 2B.

	Distractor condition			
	Incompatible	**Neutral**	**Compatible**	**Absent**
Experiment 2A				
Low load	5.22 (0.99)	2.18 (0.58)	3.48 (0.69)	3.06 (0.67)
High load	5.90 (1.04)	5.66 (1.08)	8.33 (1.96)	4.58 (0.67)
Experiment 2B				
Low load	3.69 (0.59)	2.95 (0.64)	2.87 (0.89)	3.37 (0.65)
High load	5.81 (1.18)	5.41 (1.08)	5.81 (1.12)	4.01 (0.80)

(Standard errors appear in parentheses).

$F_{(1, 16)} = 24.10$, $p < 0.001$, $\eta_p^2 = 0.60$, with RTs in the incompatible distractor condition (1074 ms) being slower than RTs in the neutral distractor condition (1010 ms). Most importantly, consistent with the findings reported by Biggs and Gibson (2010, Experiment 2), the interaction between these two variables did not approach significance ($F < 1$), suggesting that the salient distractor captured focal attention under both low and high perceptual load. An identical within-subjects ANOVA was performed on error rates, but neither the main effects nor the interaction approached significance (all Fs < 1). Thus, the RT results do not appear to be compromised by a speed-accuracy trade-off.

Singleton distractor presence

A 2 × 2 within-subjects ANOVA was conducted on mean correct RTs with perceptual load (low load vs. high load) and singleton distractor presence (present vs. absent) as the two within-subjects variables. As expected, there was a significant main effect of perceptual load, $F_{(1, 16)} = 213.03$, $p < 0.001$, $\eta_p^2 = 0.93$, with faster RTs in the low load condition (624 ms) than in the high load condition (1264 ms). More importantly, consistent with the attentional capture interpretation of the singleton distractor compatibility effect, there was also a significant main effect of singleton distractor presence, $F_{(1, 16)} = 61.92$, $p < 0.001$, $\eta_p^2 = 0.80$, indicating a 133 ms search-time cost in the singleton distractor present condition relative to the absent condition. Note, however, that these main effects were qualified by a significant perceptual load × singleton distractor presence interaction, $F_{(1, 16)} = 38.64$, $p < 0.001$, $\eta_p^2 = 0.71$. Although the pattern of singleton distractor compatibility effects reported above suggested that the color singleton captured attention equally well across the low- and high load conditions, this interaction indicated that the presence of the singleton slowed search more in the high load condition [N − A = 208 ms, $p < 0.001$] than in the low load condition [N − A = 58 ms, $t_{(16)} = 3.84$, $p < 0.001$], perhaps because the color singleton appeared more salient when it appeared among 11 commonly-colored items than when it appeared among three commonly-colored items. At any rate, this significant interaction is contrary to the predictions of the perceptual load account.

An identical within-subjects ANOVA was performed on error rates. Neither the main effects, nor the interaction approached significance (all Fs < 1). Thus, the RT results do not appear to be compromised by a speed-accuracy trade-off.

DISCUSSION

Consistent with previous evidence (Biggs and Gibson, 2010, Experiment 2), the present study suggested that color salience can dominate perceptual load by providing converging evidence through both singleton distractor presence and singleton distractor compatibility. Moreover, the search-time cost associated with singleton distractor presence was larger in high load than low load, which might reflect the larger role of salience in the high load condition. Thus, the consistent effect of singleton distractor compatibility observed in the present study does not appear to arise as result of the interplay between distractor dilution and exposure duration.

EXPERIMENT 2B

The consistent effects of singleton distractor compatibility and presence observed in Experiment 2A were interpreted to reflect the capture of focal attention by the salient distractor. Recall that Biggs and Gibson (2010) considered this pattern of results to be unusual given that the effect of distractor compatibility observed in the high load condition of their experiments increased as observers' knowledge of display load increased, whereas the effect of distractor compatibility observed in the low load condition remained constant regardless of observers' knowledge of display load. Our previous work interpreted the change in the magnitude of the distractor compatibility effect from one knowledge context to the other as reflecting the operation of top-down strategies, even though most previous evidence has suggested that attentional capture by salient singletons typically decreases as task knowledge increases (e.g., Lamy and Yashar, 2008; Müller et al., 2009).

However, another possibility is that rather than developing effective distractor suppression strategies, the task context is actually biasing the observer toward processing the distractor. An alternative means of ignoring the distractor is effectively allocating attention to relevant information rather than suppressing irrelevant information. Experiment 2B was therefore conducted to determine if the irrelevant singleton distractor would have less effect on performance if it was only encountered after experience with singleton distractor absent trials. If the order in which the irrelevant singleton was encountered is important, then the magnitude of the singleton distractor compatibility and presence effects should be significantly reduced in the high load condition. Such evidence would be important because it would corroborate the notion that these effects are not driven in a purely stimulus-driven fashion in this paradigm, and may shed light on the nature of the attention allocation strategies that observers use to modulate the effects of distractor salience.

METHOD

Participants

Eighteen undergraduate students from the University of Notre Dame participated in the experiment for partial completion of a course requirement. Data from two observers were removed due to an error rate over 20%. All observers reported normal or corrected-to-normal visual acuity without color deficits.

Stimuli and apparatus

The search displays were identical to Experiment 2A.

Procedure

The procedure was identical to Experiment 2A, with the sole exception being that blocks of distractor absent trials always preceded blocks of distractor present trials within each load condition in Experiment 2. Half of the observers saw this order: high load, distractor absent; high load, distractor present; low load, distractor absent; low load, distractor present. The other half of the observers saw this order: low load, distractor absent; low load, distractor present; high load, distractor absent; high load, distractor present.

RESULTS

Mean correct RTs are shown in the bottom panel of **Figure 4** as a function of perceptual load and distractor condition. Corresponding error rates are shown in **Table 2**.

Singleton distractor compatibility

A 2 × 2 within-subjects ANOVA was conducted on mean correct RTs with perceptual load (low load vs. high load) and singleton distractor compatibility (incompatible vs. neutral) as the two within-subjects variables. There was a significant main effect of perceptual load, $F_{(1, 15)} = 58.34$, $p < 0.001$, $\eta_p^2 = 0.80$, with faster RTs in the low load condition (666 ms) than in the high load condition (1200 ms); and, there was also a marginally significant main effect of singleton distractor compatibility, $F_{(1, 15)} = 4.02$, $p = 0.063$, $\eta_p^2 = 0.21$, with RTs in the incompatible distractor condition (947 ms) being slower than RTs in the neutral distractor condition (919 ms). Most importantly, however, these results were qualified by a significant perceptual load X singleton distractor compatibility interaction, $F_{(1, 15)} = 6.65$, $p < 0.025$, $\eta_p^2 = 0.31$, which indicated a larger compatibility effect in the low load condition [I – N = 62 ms, $t_{(15)} = 8.29$, $p < 0.001$] than in the high load condition [I − N = −7 ms, $p > 0.5$].

An identical within-subjects ANOVA was performed on error rates. There was a significant main effect of perceptual load $F_{(1, 15)} = 13.30$, $p < 0.01$, $\eta_p^2 = 0.47$, with fewer errors committed in the low load condition (3.70%) than in the high load condition (5.78%); and, there was also a significant main effect of singleton distractor compatibility, $F_{(1, 15)} = 6.47$, $p < 0.025$, $\eta_p^2 = 0.30$, with fewer errors committed in the neutral distractor condition (3.92%) than in the incompatible distractor condition (5.56%). The interaction between these two variables was also marginally significant $F_{(1, 15)} = 3.55$, $p = 0.079$, $\eta_p^2 = 0.19$, indicating a larger compatibility effect in the low load condition [I − N = 3.04%, $t_{(15)} = 3.58$, $p < 0.01$] than in the high load condition [I − N = 0.24%, $p > 0.5$]. Hence, these findings do not compromise the RT findings reported above.

Contrary to the findings reported in Experiment 2A, the present findings suggest that perceptual load dominated salience when observers did not encounter the salient singleton until the second (and fourth) block of trials. Further evidence for the conclusion that the salient distractor had a different effect on visual search in the high load condition across Experiments 2A and 2B was sought by conducting a 2 × 2 mixed ANOVA on mean correct RTs with singleton distractor compatibility (incompatible vs. neutral) as the sole within-subjects variable and experiment (Experiment 2A vs. 2B) as the sole between-subjects variable. This analysis revealed a marginally significant singleton distractor compatibility × experiment interaction, $F_{(1, 31)} = 4.22$, $p = 0.05$, $\eta_p^2 = 0.12$, indicating that the compatibility effect was significantly larger in the high load condition of Experiment 2A (66 ms) relative to the high load condition of Experiment 2B (−7 ms).

Singleton distractor presence

A 2 × 2 within-subjects ANOVA was conducted on mean correct RTs with perceptual load (low load vs. high load) and singleton distractor presence (present vs. absent) as the two within-subjects variables. There was significant main effect of perceptual load, $F_{(1, 15)} = 99.92$, $p < 0.001$, $\eta_p^2 = 0.87$, with faster RTs in the low load condition (627 ms) than in the high load condition (1196 ms). However, neither the main effect of singleton distractor presence, nor the interaction between perceptual load and singleton distractor presence approached significance (both Fs < 1).

An identical within-subjects ANOVA was performed on error rates. There was a significant main effect of perceptual load $F_{(1, 15)} = 18.83$, $p < 0.001$, $\eta_p^2 = 0.56$, with fewer errors committed in the singleton distractor absent condition (2.62%) than in the present condition (5.12%). However, neither the main effect of singleton distractor presence, nor the interaction between perceptual load and singleton distractor presence approached significance (both Fs < 1), indicating that observers did not trade accuracy for speed.

Further evidence for the conclusion that the salient distractor had a different effect on visual search in the high load condition across Experiments 2A and 2B was sought by conducting a 2 × 2 mixed ANOVA on mean correct RTs with singleton distractor presence (present vs. absent) as the sole within-subjects variable and experiment (Experiment 2A vs. 2B) as the sole between-subjects variable. This analysis revealed a significant singleton distractor presence × experiment interaction, $F_{(1, 31)} = 19.41$, $p < 0.001$, $\eta_p^2 = 0.39$, indicating that the presence effect was significantly larger in the high load condition of Experiment 2A (208 ms) relative to the high load condition of Experiment 2B (16 ms).

Note that we also considered the possibility that the differential pattern of distractor presence effects observed across Experiments 2A and 2B might reflect the interplay between two processes: capture and practice. Some participants (those in the singleton distractor present first condition) had more practice than other participants (those in the singleton distractor absent first condition) when performing search on singleton absent trials. It is possible the large differences observed between the experiments are not solely due to differential processing of the singleton distractor, but the differences are so large because practice speeded response times for some participants and not others. Response time differences are our primary measure of distractor interference, and the change could be due to either slower responses in the presence of the critical distractor or a speeding of responses in the singleton absent trials. If search in the present study was subject to robust practice effects, we would expect to observer a significant difference in response times for the singleton absent trials between the two experiments. This analysis was performed on singleton absent trials and not singleton present trials because singleton present trials are potentially subject to differential processing of the critical distractor; singleton absent trials do not include the same confound. However, RTs during the singleton distractor absent trials were nearly identical in both Experiments 2A and 2B ($p > 0.50$) despite the increased practice the observers had when they encountered the distractor present blocks first (Experiment 2A).

DISCUSSION

In summary, Experiment 2B was identical to Experiment 2A with the sole exception that the observers did not encounter the salient distractor until the second (and fourth) trial blocks. However, contrary to the results of Experiment 2A, the results obtained in Experiment 2B suggested that perceptual load now dominated visual salience in the competition for visual selective attention. Singleton distractor compatibility analyses suggested that the incompatible distractor produced interference in the low load condition but not in the high load condition. Results of the presence effects corroborated this conclusion by suggesting that the presence of the singleton distractor did not cause a search-time cost in either load condition. This evidence suggests that the interplay between salience, dilution, and perceptual load in visual selection depends highly upon top-down factors such as task context and prior experience. We confirmed this conclusion by conducting a 3 × 2 repeated measures ANOVA with experiment (1, 2A, and 2B) as a between-subjects factor and singleton distractor condition (incompatible, neutral, or absent) as the within-subjects factor. See **Figure 5** for results. The difference across experiments was non-significant for low perceptual load, $F_{(4,\ 100)} = 1.74$, $p = 0.15$, but the difference across experiments was significant for high perceptual load $F_{(4,\ 100)} = 16.85$, $p < 0.001$. Therefore, top-down factors have a much greater impact under high vs. low perceptual load conditions.

GENERAL DISCUSSION

The present study provides several important contributions to our understanding of visual selective attention. First, by including two measures of distractor processing—singleton distractor compatibility and singleton distractor presence—the present study was able to provide two converging sources of evidence for its theoretical conclusions. This converging evidence was deemed necessary because recent developments have raised the possibility that the outcome of a single measure might not adequately disambiguate the various factors at work. Second, the present study also clarified the extent to which visual salience can dominate the control of focal attention during visual selection in this serial search task. Recall that previous studies using this paradigm had concluded that the dominance of visual salience over perceptual load was context-dependent (Biggs and Gibson, 2010). However, this pattern of dominance was puzzling given that the

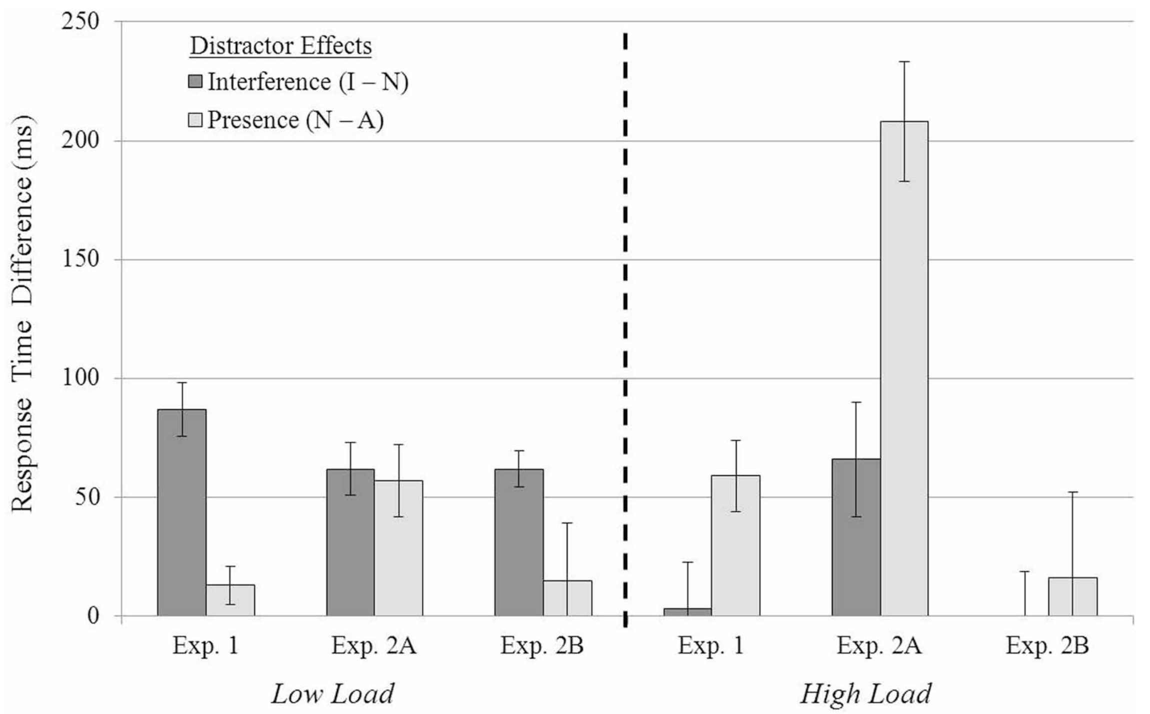

FIGURE 5 | Mean distractor interference (Incompatible − Neutral) and distractor presence (Neutral − Absent) effects shown as a function of perceptual load across experiments. Error bars reflect the standard error of the mean.

effect of salience appeared to become stronger in high load contexts despite increased knowledge of display characteristics. In contrast, other studies (see e.g., Lamy and Yashar, 2008; Müller et al., 2009; but see, Pinto et al., 2005) have typically shown that the effects of salience become weaker as knowledge of display characteristics increased. Contrary to these previous efforts, the present study attempted to manipulate context without altering the amount of display knowledge provided to observers. However, the critical manipulation under these circumstances appears to be the exposure or experience with singleton distractor absent trials. Findings obtained in Experiment 2A suggested that observers could not ignore the salient distractor, which could lead to the conclusion that visual salience dominated perceptual load. The findings obtained in Experiment 2B suggested that observers could ignore the salient distractor, which could lead to the conclusion that perceptual load dominated visual salience. The critical difference hinges upon blocking and prior exposure (or lack thereof) to the singleton distractor.

How might this relative ordering of singleton presence modulate the effects of a salient distractor? Current evidence suggests that the effect of salient distractors on attention can be modulated by the width of the attentional window, which in turn can be modulated by the type of search task observers are asked to perform (Gibson and Peterson, 2001; Theeuwes, 2004; Belopolsky et al., 2007). More specifically, the computation of visual salience typically requires the computation of a "difference signal" (Cave and Wolfe, 1990), which reflects the difference between each display item and all other display items along each feature dimension. Such computation appears to require that observers distribute their attention broadly across the display, such as when observers search for relevant singleton targets during singleton detection tasks (Theeuwes, 1991, 1992, 1994). After all, why would a red distractor pop-out from a homogenous green background if not for some processing of the background itself? Under these conditions, irrelevant singletons distractors typically capture attention so long as they are more salient than the relevant singleton targets (Theeuwes, 1991); though, there has been debate about whether the broad distribution of attention is sufficient for attentional capture, or whether it is also necessary for observers to engage in a particular type of feature processing strategy (e.g., singleton detection) while their attention is broadly distributed (for further discussion, see Bacon and Egeth, 1994; Lamy and Egeth, 2003; Theeuwes, 2004; Leber and Egeth, 2006a,b). In contrast, the visual salience of any given display item may not be identically computed when observers distribute their attention more narrowly on individual display items, such as when observers search for non-singleton targets during serial search tasks (Gibson and Peterson, 2001; Theeuwes, 2004; Belopolsky et al., 2007). Under these conditions, irrelevant singletons distractors typically do not capture attention (Jonides and Yantis, 1988; Folk and Annett, 1994).

The primary issue then becomes these two potential attentional allocation strategies that the observer might employ during search: broadly or narrowly tuned attention. On the one hand, observers might have an initial tendency to distribute their attention broadly across the display when the salient distractor is present, perhaps because they seek to first detect the singleton in order to subsequently avoid it during search. In so doing, they would utilize a search strategy that causes their attention to be captured by the salient distractor. Furthermore, once the salient distractor was located, observers would then need to distribute their attention more narrowly on individual display items within the relevant set in order to find the target. On the other hand, observers might have a tendency to only distribute their attention more narrowly on individual display items when the salient distractor would never be present.

In addition to the possibility that the distractor present and distractor absent conditions might be associated with two different attention allocation strategies, it is also possible that the attention allocation strategy used during a preceding block of trials might persist during a subsequent block of trials. Consistent with this notion, Leber and Egeth (2006a,b) have shown that observers who were forced to engage in one of two feature processing strategies—feature search or singleton detection—during an initial training phase continued to adopt that strategy during a subsequent test phase in which either strategy could have been used. Moreover, Leber and Egeth (2006a) also showed that the trained strategy was more likely to persist during the test phase following 320 training trials than following 40 training trials.

Similar to training effects, how observers distributed their attention during blocks of singleton distractor present trials may have depended on the amount of prior experience they had searching distractor absent displays. In other words, observers may have been more likely to distribute their attention narrowly during singleton distractor present trials as their exposure to singleton distractor absent trials increased. If so, then observers may not have relied as heavily upon locating the singleton distractor during a brief, but broadly tuned initial processing phase, leading to a reduction in attentional capture and ultimately distractor interference. Conversely, observers may also have been more likely to distribute their attention broadly during singleton distractor absent trials as their exposure to singleton distractor present trials increased. There would have been no observable consequences of distractor interference in this case as there was no singleton distractor present to provide interference, and we did observer similar overall response times for singleton distractor absent trials in both Experiments 2A and 2B. Furthermore, according to Leber and Egeth (2006a), the adoption of a particular attention allocation strategy becomes increasingly automated as task performance becomes increasingly associated with a particular attention allocation strategy. In this view, the present findings may be interpreted to suggest that observers' application of the narrow attention allocation strategy became more automatic as their exposure to the "training" (i.e., singleton distractor absent) task increased. Note, however, that whereas Leber and Egeth always presented blocks of training trials before blocks of test trials in their study, blocks of "training" (i.e., singleton distractor absent) trials were alternated with blocks of "test" (i.e., singleton distractor present) trials in the present study. Thus, the adoption of a broad attention allocation strategy could have competed with the adoption of a narrow attention allocation strategy in the present study because both could have been increasingly associated with task performance over time.

In conclusion, previous research has suggested that the competition between perceptual load and visual salience can be biased as a function of task context (Biggs and Gibson, 2010). Our present experiments extend this idea and provide an example of what may be included within the scope of "context." Specifically, certain processing strategies may be experience-dependent and will lead the observer to adopting a narrow attentional set. This evidence supports an interpretation of attentional capture as a top-down effect. Therefore, even when capture appears to be dependent on salience, it can actually be the product of a processing strategy that prioritizes relative salience. The full extent to which an observer becomes biased toward a particular processing strategy, and the extent to which it transfers to different search displays, is a subject that requires further research.

REFERENCES

Bacon, W. F., and Egeth, H. E. (1994). Overriding stimulus-driven attentional capture. *Percept. Psychophys.* 55, 485–496. doi: 10.3758/BF03205306

Belopolsky, A. V., Zwaan, L., Theeuwes, J., and Kramer, A. F. (2007). The size of an attentional window modulates attentional capture by color singletons. *Psychon. Bull. Rev.* 14, 934–938. doi: 10.3758/BF03194124

Benoni, H., and Tsal, Y. (2010). Where have we gone wrong? Perceptual load does not affect selective attention. *Vision Res.* 50, 1292–1298. doi: 10.1016/j.visres.2010.04.018

Biggs, A. T., and Gibson, B. S. (2010). Competition between color salience and perceptual load during visual selection can be biased by top-down set. *Atten. Percept. Psychophys.* 72, 53–64. doi: 10.3758/APP.72.1.53

Biggs, A. T., and Gibson, B. S. (in press). Visual salience can co-exist with dilution during visual selection. *J. Exp. Psychol. Hum. Percept. Perform.*

Broadbent, D. E. (1958). *Perception and Communication.* London: Pergamon. doi: 10.1037/10037-000

Cave, K. R., and Wolfe, J. M. (1990). Modelling the role of parallel processing in visual search. *Cogn. Psychol*. 22, 225–271. doi: 10.1016/0010-0285(90)90017-X

Chun, M. M., and Jiang, Y. (1998). Contextual cueing: implicit learning and memory of visual context guides spatial attention. *Cogn. Psychol*. 36, 28–71. doi: 10.1006/cogp.1998.0681

Chun, M. M., and Jiang, Y. (1999). Top-down attentional guidance based on implicit learning of visual covariation. *Psychol. Sci.* 10, 360–365. doi: 10.1111/1467-9280.00168

Cosman, J. D., and Vecera, S. P. (2010). Attentional capture under high perceptual load. *Psychon. Bul. Rev.* 17, 983–986. doi: 10.3758/PBR.17.6.815

Deutsch, J. A., and Deutsch, D. (1963). Attention: Some theoretical considerations. *Psychol. Rev*. 70, 80–90. doi: 10.1037/h0039515

Dixon, M. L., Ruppel, J., Pratt, J., and De Rosa, E. (2009). Learning to ignore: acquisition of sustained attentional suppression. *Psychon. Bull. Rev.* 16, 418–423. doi: 10.3758/PBR.16.2.418

Eltiti, S., Wallace, D., and Fox, E. (2005). Selective target processing: perceptual load or distractor salience? *Percept. Psychophys*. 67, 876–885. doi: 10.3758/BF03193540

Folk, C., and Annett, S. (1994). Do locally defined feature discontinuities capture attention? *Percept. Psychophys*. 53, 277–287. doi: 10.3758/BF03209762

Forster, K. I., and Forster, J. C. (2003). DMDX: a Windows display program with millisecond accuracy. *Behav. Res. Methods Instrum. Comput*. 35, 116–124. doi: 10.3758/BF03195503

Gibson, B. S., and Bryant, T. A. (2008). The identity intrusion effect: attentional capture or perceptual load? *Vis. Cogn*. 16, 182–199. doi: 10.1080/13506280701467987

Gibson, B. S., and Peterson, M. A. (2001). "Inattentional capture and attentional capture: evidence for attention-based theories of visual salience," in *Attraction, Distraction, and Action: Interdisciplinary Perspectives on Attentional Capture,* eds C. L. Folk and B. S. Gibson (Oxford: Elsevier), 51–76. doi: 10.1016/S0166-4115(01)80005-4

Gibson, B. S., Scheutz, M., and Davis, G. J. (2009). Symbolic control of visual attention: semantic constraints on the spatial distribution of attention. *Atten. Percept. Psychophys*. 71, 363–374. doi: 10.3758/APP.71.2.363

Johnson, D. N., McGrath, A., and McNeil, C. (2002). Cuing interacts with perceptual load in visual search. *Psychol. Sci*. 13, 284–287. doi: 10.1111/1467-9280.00452

Jonides, J., and Yantis, S. (1988). Uniqueness of abrupt visual onset in capturing attention. *Percept. Psychophys*. 43, 346–354. doi: 10.3758/BF03208805

Kelley, T. A., and Yantis, S. (2009). Learning to attend: Effects of practice on information selection. *J. Vis.* 9, 1–18. doi: 10.1167/9.7.16

Lamy, D., and Egeth, H. E. (2003). Attentional capture in singleton-decection and feature-search modes. *J. Exp. Psychol. Hum. Percept. Perform*. 29, 1003–1020. doi: 10.1037/0096-1523.29.5.1003

Lamy, D., and Yashar, A. (2008). Intertrial target-feature changes do not lead to more distraction by singletons: target uncertainty does. *Vision Res*. 48, 1274–1279. doi: 10.1016/j.visres.2008.02.021

Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. *J. Exp. Psychol. Hum. Percept. Perform*. 21, 451–468. doi: 10.1037/0096-1523.21.3.451

Lavie, N. (2005). Distracted and confused? Selective attention under load. *Trends Cogn. Sci*. 9, 75–82. doi: 10.1016/j.tics.2004.12.004

Lavie, N. (2006). The role of perceptual load in visual awareness. *Brain Res*. 1080, 91–100. doi: 10.1016/j.brainres.2005.10.023

Lavie, N., and Cox, S. (1997). On the efficiency of visual selective attention. *Psychol. Rev*. 76, 282–299.

Lavie, N., Hirst, A., deFockert, J. W., and Viding, E. (2004). Load theory of selective attention and cognitive control. *J. Exp. Psychol. Gen.* 133, 339–354. doi: 10.1037/0096-3445.133.3.339

Lavie, N., and Tsal, Y. (1994). Perceptual load as a major determinant of the locus of selection in visual attention. *Percept. Psychophys*. 56, 183–197. doi: 10.3758/BF03213897

Leber, A. B., and Egeth, H. E. (2006a). Attention on autopilot: past experience and attentional set. *Vis. Cogn*. 14, 565–583.

Leber, A. B., and Egeth, H. E. (2006b). It's under control: top–down search strategies can override attentional capture. *Psychon. Bull. Rev*. 13, 132–138.

Müller, H. J., Geyer, T., Zehetleitner, M., and Krummenacher, J. (2009). Attentional capture by salient color singletons distractors is modulated by top-down dimensional set. *J. Exp. Psychol. Hum. Percept. Perform*. 35, 1–16. doi: 10.1037/0096-1523.35.1.1

Paquet, L., and Craig, G. L. (1997). Evidence for selective target processing with a low perceptual load flankers task. *Mem. Cogn.* 25, 182–189. doi: 10.3758/BF03201111

Pinto, Y., Olivers, C. N. L., and Theeuwes, J. (2005). Target uncertainty does not lead to more distractor by singletons: intertrial priming does. *Percept. Psychophys*. 67, 1354–1361. doi: 10.3758/BF03193640

Theeuwes, J. (1990). Perceptual selectivity is task dependent: Evidence from selective search. *Acta Psychologica* 74, 81–99. doi: 10.1016/0001-6918(90)90036-F

Theeuwes, J. (1991). Cross-dimensional perceptual selectivity. *Percept. Psychophys*. 50, 184–193. doi: 10.3758/BF03212219

Theeuwes, J. (1992). Perceptual selectivity for color and form. *Percept. Psychophys*. 51, 599–606. doi: 10.3758/BF03211656

Theeuwes, J. (1994). Stimulus-driven capture and attentional set: selective search for color and visual abrupt onsets. *J. Exp. Psychol. Hum. Percept. Perform*. 20, 799–806. doi: 10.1037/0096-1523.20.4.799

Theeuwes, J. (2004). Top-down search strategies cannot override attentional capture. *Psychon. Bull. Rev*. 11, 65–70. doi: 10.3758/BF03206462

Theeuwes, J., Atchley, P., and Kramer, A. F. (2000). "On the time course of top-down and bottom-up control of visual attention," in *Control of Cognitive Processes: Attention and Performance XVIII*, eds S. Monsell and J. Driver (A Bradford Book), 105–124.

Theeuwes, J., and Burger, R. (1998). Attentional control during visual search: the effect of irrelevant singletons. *J. Exp. Psychol. Hum. Percept. Perform*. 24, 1342–1353. doi: 10.1037/0096-1523.24.5.1342

Tsal, Y., and Benoni, H. (2010). Diluting the burden of load: perceptual load effects are simply dilution effects. *J. Exp. Psychol. Hum. Percept. Perform*. 36, 1645–1656. doi: 10.1037/a0018172

Tsal, Y., and Makovski, T. (2006). The attentional white bear phenomenon: the mandatory allocation of attention to expected distractor locations. *J. Exp. Psychol. Hum. Percept. Perform.* 32, 351–363. doi: 10.1037/0096-1523.32.2.351

Vatterott, D., and Vecera, S. (2012). Attentional Capture is attenuated after experience with diverse distractor features. *J. Vis.* 12, 1339. doi: 10.1167/12.9.1339

Wilson, D. E., Muroi, M., and MacLeod, C. M. (2011). Dilution, not load, affects distractor processing. *J. Exp. Psychol. Hum. Percept. Perform*. 37, 319–335. doi: 10.1037/a0021433

Zehetleitner, M., Goschy, H., and Müller, H. J. (2012). Top-down control of attention: it's gradual, practice-dependent, and hierarchically organized. *J. Exp. Psychol. Hum. Percept. Perform*. 38, 941–957. doi: 10.1037/a0027629

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Competition explains limited attention and perceptual resources: implications for perceptual load and dilution theories

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Both perceptual load theory and dilution theory purport to explain when and why task-irrelevant information, or so-called distractors are processed. Central to both explanations is the notion of limited resources, although the theories differ in the precise way in which those limitations affect distractor processing. We have recently proposed a neurally plausible explanation of limited resources in which neural competition among stimuli hinders their representation in the brain. This view of limited capacity can also explain distractor processing, whereby the competitive interactions and bias imposed to resolve the competition determine the extent to which a distractor is processed. This idea is compatible with aspects of both perceptual load and dilution models of distractor processing, but also serves to highlight their differences. Here we review the evidence in favor of a biased competition view of limited resources and relate these ideas to both classic perceptual load theory and dilution theory.

Keywords: perceptual load, competition, dilution, limited capacity, limited resources

INTRODUCTION

"Everyone knows what attention is . . . it implies withdrawal from some things in order to deal effectively with others" (James, 1890). For over a century, psychologists have understood that the primary problem with attention is that we do not have enough of it; we simply cannot process and respond to all the information in the environment that may be relevant to our current task (e.g., Jersild, 1927; Cherry, 1953; Welford, 1957; Broadbent, 1958; Sperling, 1960; Eriksen and St. James, 1986; Pylyshyn and Storm, 1988; Raymond et al., 1992; Pashler, 1994); nor can we completely inhibit distracting information (e.g., Stroop, 1935; Treisman, 1960; Eriksen and Eriksen, 1974). More recent research has sought to understand the neural basis of our limited attentional capacity, and has revealed neural limits in our capacity to prioritize (e.g., Mecklinger et al., 2003), encode into working memory (e.g., Todd and Marois, 2004; Scalf et al., 2007, 2011b), and respond to task-relevant material (e.g., dual task interference Dux et al., 2006; Erickson et al., 2007).

The prevailing model and thus investigations of our limited capacity to attend to multiple items have focused on our limited attentional resources (e.g., Intriligator and Cavanagh, 2001; Lavie and Robertson, 2001; Mitchell and Cusack, 2008; Xu and Chun, 2009). These models have suggested that it is our limited ability to simultaneously direct attention to multiple stimuli that causes our limited capacity to respond to those items. They proceed from a "resource-limited" view of attentional capacity (e.g., Alvarez and Franconeri, 2007); that is, because we can select, individuate and identify any single member of a group of items, our failure to successfully perform these operations simultaneously on all members must derive from the limited resources we have to apply to them. The notion that our limited attentional capacity is caused by limited attentional resources has both implicitly and explicitly informed research for well over a century, effectively constraining questions about attentional function to those concerned with the "resources" that direct attention.

COMPETITION FOR REPRESENTATION INSTEAD OF LIMITED RESOURCES

Exactly what is an "attentional resource"? One definition has been "regulatory juice" (Mozer and Sitton, 1998) but exchanging the word "juice" for "resource" is not particularly helpful. Some models of "resources" compare them to a power supply (Kahneman, 1973), such as the amount of gas available to a cooking range. But what would the neural equivalent of "gas" be? Although severe glucose restriction (Ståhle et al., 2011) or oxygen depletion (such as at high altitude; Kramer et al., 1993) can indeed impair cognitive function, low-levels of neither of these metabolites appear to be responsible for the attentional limitations experienced by well-nourished individuals at sea-level. Nor is it the case that attentional limitations are caused by a number of neurons insufficient to represent task-relevant material and cognitive functions. Historically, resources have been sometimes referred to as occurring in "pools"; that is the extent to which these "pools" are available determines the extent to which they may be simultaneously applied to different stimuli or tasks (Wickens, 1984; Wickens et al., 1984). Such theories attempt to separate the "pools" by processing modality, positing that separable sensory (visual, auditory) or cognitive (verbal, spatial) operations will not limit each other because they rely on different regions of neural tissue. At first glance, this may appear to be a sensible heuristic for defining a resource. But consider the vast amount of neural tissue dedicated to processing of visual stimuli; not only are the full visual fields represented many times over, at many spatial scales, but regions broadly specialized for processing certain classes of stimuli (e.g., faces, places, objects) share relatively little neural overlap (Malach et al., 1995; Kanwisher et al., 1997; Epstein and Kanwisher, 1998). And yet, it is still very difficult for us to simultaneously attend to one house and one face (Reddy et al., 2009). What then is the neural basis of this limited processing capacity?

Critically, neither individual neurons nor neural populations operate in isolation. Instead, they have continuous, mutually modulatory interactions; the response of two individual neurons with different receptive fields (RF) that are filled with different stimuli may each be modified by the stimuli outside of their own RF as a result of the neurons' inhibitory or excitatory interactions (e.g., Blakemore and Tobin, 1972; DeAngelis et al., 1992; Desimone and Duncan, 1995; Pelli, 2008). The ability of neural interactions to dramatically influence visual perception has been well-articulated by models of competition for representation (Desimone and Duncan, 1995) and divisive normalization (Reynolds and Heeger, 2009). Specifically, although adjacent visual information may simultaneously fall within the RF of adjacent, but separate cell populations early in visual processing (e.g., V1), the output of the high resolution cells will ultimately converge on a single population of cells at higher level of visual cortex (Gattass et al., 1988), at which point they will interact in a mutually inhibitory manner. For example, two stimuli presented simultaneously within the same RF of a V4 cell evoke less activity than the summed activity of each individual stimulus presented alone (Chelazzi et al., 1998; Reynolds et al., 1999). Similarly, four neighboring stimuli presented simultaneously, and thus capable of competing with each other through mutually inhibitory interactions, evoke lower blood oxygen level dependent (BOLD) responses in V4 than the same stimuli presented sequentially and thus unable to compete (Kastner et al., 1998, 2001; Beck and Kastner, 2005, 2007). Moreover, the magnitude of this difference, which can be viewed as an index of competition, varies as a function of the distance among the stimuli (Kastner et al., 2001) and scales with RF size across visual cortex (Kastner et al., 1998, 2001; Beck and Kastner, 2005, 2007) suggesting that inhibitory interactions among multiple stimuli are strongest when they are likely to fall simultaneously within the same RF. The result of these inter-stimulus interactions is that representations of stimuli presented simultaneously are weaker and coarser than those of stimuli presented alone. Even though these visual stimuli are represented by different cells in both the retina and early levels of visual processing, these representations are mutually modulatory, and thus cannot be said to be "separable."

What happens when we need the full detail of the visual stimulus to guide behavior? Attention biases the competitive or normalization process in favor of task-relevant material (Desimone and Duncan, 1995; Reynolds and Heeger, 2009), allowing that information to dominate the neural response at the expense of task-irrelevant material. Directing attention to one of multiple stimuli therefore eliminates or reduces the suppressive influences of nearby stimuli, consistent with the idea that selective attention biases the competition among multiple stimuli in favor of the attended stimulus (Moran and Desimone, 1985; Luck et al., 1997; Kastner et al., 1998; Reynolds et al., 1999; Recanzone and Wurtz, 2000). For example, when a monkey directs attention to one of two competing stimuli within a RF, the responses in extrastriate areas V2, V4, and MT are similar to those evoked by that stimulus presented alone (Reynolds et al., 1999; Recanzone and Wurtz, 2000). Similarly, directing attention to one of four neighboring stimuli pushes the extrastriate BOLD activity evoked by simultaneously (potentially competing) stimuli closer to that of the sequentially presented (non-competing) stimuli (Kastner et al., 1998, 2001). These findings suggest that when attention is directed to an item, its representation is protected from the inhibitory influences of unattended stimuli.

Importantly, however, this protection breaks down when attention is directed to multiple competing objects simultaneously. Our work has demonstrated that if attention is directed to multiple items, competitive interactions among them impair their representation. In other words, competition for representation not only limits initial processing, but also our capacity to effectively attend to multiple items (Scalf and Beck, 2010; Scalf et al., 2011a). Consider the case when attention might be directed to simultaneously enhance the representations of multiple competing stimuli. No single stimulus would receive a boost that would enable it to dominate the competitive process; instead, signals from cells whose RFs contained more than one attended item would continue to reflect the contribution of all of the simultaneously attended items. Because attention would be unable to reduce the inhibitory interactions among multiple attended items, the representations of attended items would be weaker than would be the case if a single item received attention. Our previous research has confirmed this prediction (Scalf and Beck, 2010). The receptive field sizes of V4 cells in humans appear to be between 4° and 6° (Kastner et al., 2001); when we asked participants to view multiple adjacent items subtending 2°, we found that BOLD signal evoked in V4 by an attended item was weaker if two neighboring items were also attended rather than ignored. In fact, in another experiment we showed that simultaneously attending to multiple stimuli produced no measurable effect on competitive interactions among attended stimuli (Scalf et al., 2011a). Although attention did enhance V4 BOLD response to the stimulus items relative to when they were unattended, the competitive interactions (assessed by the difference in activity evoked by simultaneous and sequential presentations) were identical for attended and unattended stimuli. Critically, the cost of attending to multiple items simultaneously was specific to conditions in which the items might have required simultaneous representation by a common group of cells (Scalf and Beck, 2010). If the items were presented either sequentially or in opposite visual fields (and thus could be represented either at different times or by different cell populations), then the V4 signal evoked by the cortically isolated item was unaffected by the attentional status of its neighbors. These data demonstrate that attention is less effective at enhancing stimulus representations if it is directed to multiple competing items, suggesting that competitive interactions among stimuli are one cause of humans' limited attentional capacity. Similar arguments can be made regarding multiple salient stimuli, biased via bottom up mechanisms (West et al., 2010).

Although our fMRI data were the first to explicitly link limited attentional capacity to competition for representation (Scalf and Beck, 2010), we were not the first to make such predictions. Nearly two decades of behavioral research support the notion that attentional capacity is functionally expanded when multiply attended items are positioned such that they do not compete for representation. Although not interpreted within the biased competition framework, Sagi and Julez (1985) found that the ability to identify simultaneously presented letters increases with their increasing spatial separation, while Cohen and Ivry (1991) reported that visual search displays containing identical number of items were searched more efficiently when items were widely spaced rather than clumped together. When asked to report two cued letters within a circular 24-item backward masked array, observers are increasingly less accurate as the spatial distance between the cued items is decreased (Bahcall and Kowler, 1999). Similarly, the speed with which observers can make judgments about two cued stimuli (interspersed among fillers) is inversely proportional to the distance between those stimuli; the greater the separation between the attended stimuli, the faster participants are able to respond to them (McCarley et al., 2004, 2007; Mounts and Gavett, 2004; Hilimire et al., 2010). McCarley, Mounts and colleagues explicitly propose that these findings result from the failure of visual cortex to represent multiple attended items that are positioned in a way to compete for representation. Reddy and VanRullen (2007) also appeal to competition in visual cortex to explain why search performance in facial discrimination task improves as the spacing between items increases. The number of moving objects that may be tracked (Alvarez and Franconeri, 2007; Shim et al., 2008; Franconeri et al., 2010) and the number of locations that may be simultaneously monitored for target information (Kristjánsson and Nakayama, 2002; Franconeri et al., 2007) also increases with increasing interstimulus distance, and these data have also recently been interpreted as reflecting competition for representation (Franconeri et al., 2013). Finally, a number of studies have demonstrated that dividing information between the two cerebral hemispheres, or isolating it anatomically from each other in other ways, functionally expands attentional capacity (Luck et al., 1989; Chelazzi et al., 2001; Alvarez and Cavanagh, 2005; Delvenne, 2005; Carlson et al., 2007; Scalf et al., 2007; Torralbo and Beck, 2008; Scalf and Beck, 2010; Alvarez et al., 2012). These behavioral findings are broadly consistent with the notion that attentional "capacity" is functionally limited when items are positioned such that their representations will evoke mutually inhibitory interactions.

Although separation in extrastriate cortex appears to expand capacity, we are not arguing that competitive interactions in extrastriate cortex are the sole source of our limited capacity. Certainly, other limitations exist (e.g., Mecklinger et al., 2003; VanRullen and Koch, 2003; Todd and Marois, 2004; Dux et al., 2006) We suggest, however, that the interactive (competitive) nature of neural representations across even seemingly distinct neural systems may determine the extent to which the information processed by those systems ultimately influences behavior. Although direct evidence of truly competitive interactions between inputs processed by separate neural subsystems is sparse, this framework has been successfully applied to a number of data sets. Neural patterns of activation that are unique to either face or house stimuli despite being anatomically separated, actively suppress one another; this suppression is resolved in favor of the stimulus class to which attention is directed (Reddy et al., 2009). The capacity of visual short term working memory (VSTM) is increased if the to-be encoded items are presented sequentially rather than simultaneously; these changes most likely reflect the improved perceptual representations and decreased attentional demands of the non-competing sequential conditions (Shapiro and Miller, 2011). Neural populations that are responsive to different stimulus modalities (visual, auditory, and tactile) also seem to interact such that visual stimuli dominate response processes unless very specific procedures are used to compensate for the asymmetric excitatory connections between non-visual and visual modalities (for a review see Spence et al., 2012). Decision making and action planning have also been posited to be represented by separate neurons that ultimately compete in a winner-take-all manner to drive a motor response (Cisek, 2006, 2007, 2012). Finally, even the "separable" neural populations of the cerebral hemispheres continuously modulate one another to bias behavior in favor of one representation or another; disruption of these interactions are likely responsible for the effects of neglect and extinction that may follow damage to the parietal lobes (e.g., Rafal et al., 2006; Bays et al., 2011; De Haan et al., 2012). In summary, no matter how great the apparent separation between the neural populations that support behavior, their performance and responses are always informed and modulated by one another. As such, they cannot provide "independent attentional resources" because their activity is in fact always interdependent. We suggest that to the extent that this interdependence is competitive, these interactions will also serve to limit capacity.

IMPLICATIONS FOR PERCEPTUAL LOAD AND DILUTION THEORIES

Our conception of limited resources as competition for representation in the brain has implications for both perceptual load and dilution theories of attention. Both theories purport to explain when and why task-irrelevant information, or so-called distractors are processed. The basic phenomenon that both theories endeavor to explain is the fact that under some task conditions the to-be-ignored items continue to influence behavior, suggesting that they were not actually ignored, whereas under other task conditions the to-be-ignored items appear to be successfully suppressed. Both theories explain the presence or absence of distractor processing by relying heavily on the concept of a limited resource, although they differ in how these resource limitations subsequently affect distractor processing.

Perceptual load theory (Lavie and Tsal, 1994; Lavie, 1995, 2005, 2006, 2010; Lavie et al., 2004) was the first to unify these contrasting results under a single framework. Lavie proposed that it is the perceptual load of the relevant task that determines the extent to which "task-irrelevant," potentially distracting information is processed. When the perceptual load of the task is low (e.g., set size is small), spare attentional resources obligatorily spill over onto the to-be-ignored items and contribute to their processing. Under high perceptual load (e.g., set size is large), however, attentional resources are exhausted by the relevant task; this leaves no spare capacity for the task-irrelevant items and effectively excludes them from further processing.

Perceptual load theory has received a wealth of behavioral and neural support since its introduction (e.g., Lavie, 1995; Rees et al., 1997; Lavie et al., 2004; Beck and Lavie, 2005; Bahrami et al., 2007; Cartwright-Finch and Lavie, 2007; Forster and Lavie, 2008; Macdonald and Lavie, 2008; Remington et al., 2012). The most well-known evidence in favor of the theory, and the evidence that dilution theory takes issue with, comes from the response competition paradigm. In this paradigm participants search for a target letter and determine its identity (e.g., does the task-relevant display contain X or N?). Critically, in addition to the task-relevant set (i.e., those elements which can potentially be targets), there is a distractor letter that is compatible or incompatible with the target letter (i.e., it either matches or does not match the target). Participants are explicitly instructed to ignore this distractor. Nevertheless, its compatibility with the target can influence reaction times (RTs) to the target, indicating that the distractor's identity was processed. In keeping with perceptual load theory, this influence of the to-be-ignored item is greater in low perceptual load than high perceptual load conditions. In short, the distractor is more fully processed under conditions in which capacity is said to spill over onto the other items in the display.

Dilution theory (Benoni and Tsal, 2010, 2012; Tsal and Benoni, 2010; Wilson et al., 2011), on the other hand, posits that the critical difference between the high and low load displays is not the difficulty of the attentional task *per se* but the presence of multiple heterogeneous stimuli in the high load displays that "dilute" the effect of the distractor. Thus, the reason distractors impact behavior less in high load than in low load conditions is that there are more stimuli competing with the distractor in the high load displays, leaving the distractor a smaller share of the limited processing capacity. Tsal and Benoni (Benoni and Tsal, 2010; Tsal and Benoni, 2010) garner support for their theory by constructing what they call "high dilution/low load" displays; that is, the displays contain many competing letters (high dilution), but the target is made easier to find by virtue of its color or position, such that it qualifies as low load (i.e., detected quickly and accurately). Importantly, despite these displays being "low load" the distractor effects are virtually non-existent; that is, the RTs to targets are comparable regardless of their compatibility with the distractor letter. Tsal and Benoni take this as evidence that dilution rather than load is responsible for the diminished distractor effects.

We propose a third, alternative explanation of the classic perceptual load effect, illustrated graphically in **Figure 1** that stems from our formulation of limited resources as competition for neural representation but also shares aspects with both perceptual load and dilution theory (Torralbo and Beck, 2008). As detailed above, all display items compete for representation in visual cortex, and presumably beyond. It consequently follows that high load displays, manipulated via set size, evoke greater competition than low load displays of a smaller set size; that is, rather than being processed independently, multiple nearby stimuli mutually inhibit one another leading to a poorer representation of all stimuli. Low load displays, in contrast, are those that produce less competition among stimuli. This can be achieved with either a smaller set size (which contains fewer competing items) or homogenous non-targets that are distinct from and thus compete less with the target (e.g., pop-out displays; Lavie and Cox, 1997; Beck and Kastner, 2005). Importantly, because the greater competition evoked by high load displays impedes the representation of the target, a strong top-down bias is needed to support its representation. This strong top-down bias then results in the exclusion of the distractor and other non-target items. Under low perceptual load, however, target representation is already clear and top-down bias is unnecessary; in essence, this lack of top-down bias leaves the attentional filter (or window) open, allowing for greater distractor processing.

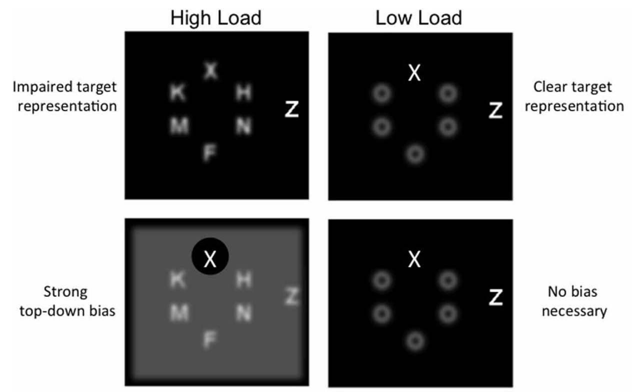

FIGURE 1 | Schematic depiction of the consequences of competition and top–down bias. Under high load, competition impairs target representation (**top** panel) and thus a top–down bias is necessary to resolve the target **(bottom)**, which in turn filters out the distractor. Under low load, the target representation is already clear (**top** panel) and thus no bias is needed to perform the task (**bottom** panel).

PERCEPTUAL LOAD AND DILUTION AS BIASED COMPETITION

How does our view of perceptual load effects as a consequence of competition and top-down bias map onto perceptual load and dilution theories? Might our conception of the neural processes underlying visual search and distractor effects help distinguish between these two theories? We note that biased competition theory has two components, and both are necessary to explain distractor processing in our view of perceptual load: first, items in a display compete for representation, and second, this competition is resolved in favor of the target (and away from other display items) through a top-down bias.

The concept of dilution maps on well to that of competition. Indeed, Tsal and Benoni (Benoni and Tsal, 2010; Tsal and Benoni, 2010) use similar "competition" language in describing the effects of dilution: when additional letters are added to the high load or high dilution displays "their features compete with those of the incongruent distractor, degrade the quality of its visual representation, thus, substantially reducing the amount of lexical analysis achieved by its corresponding lexical representation (Benoni and

Tsal, 2010, p. 1293)." Note that here Tsal and Benoni are even talking about competition at a visual feature level, consistent with known competition effects in visual cortex. The concepts of dilution and competition, however, are also compatible at later lexical and semantic levels.

Tsal and Benoni's description of the exact nature of the competition differs from our own, however. In their view the target, or potential targets, compete specifically with the distractor. In our view, however, the spatial proximity of the potential targets should result in their undergoing much greater competition than occurs between the more widely separated target and distractor (Kastner et al., 2001; Bles et al., 2006). Thus, although the task-relevant display elements may compete with and diminish the representation of the distractor at some level, we argue there is an even more important consequence of visual competition (or dilution); specifically, the target representation may be so impaired by nearby non-targets (as distinct from the response compatible or incompatible distractor) that it is no longer identifiable without selective attention. Thus, accurate identification of the target (as required by the task) requires selective attention (in the form of a top-down bias); without it, the target cannot be resolved within the visual system. According to our view, this concept of a top-down bias is both critical to explaining distractor processing and most clearly distinguishes perceptual load theory from dilution theory.

THE ROLE OF A TOP-DOWN BIAS

According to our biased competition view of distractor processing, a top-down bias is more directly responsible for the diminished distractor processing in high-load conditions than the competition among stimulus items. It is the application of this bias in favor of the target that results in diminished representation of the distractor. The top-down filter not only enhances the target but also suppresses other stimuli, including the distractor. The notion that enhancement of the target necessarily results in suppression of the other items in the display is fundamental to biased competition theory (Desimone and Duncan, 1995) and divisive inhibition more generally (Reynolds and Heeger, 2009). Because neurons representing individual items have mutually inhibitory connections, an increase in the firing rate of one results in a decrease in the other.

As currently formulated, dilution theory proposes no role for selection of task relevant material. It simply assumes a passive dilution (or competition) among the stimuli. Under high load or high dilution, the distractor receives few resources because its representation is diluted (or weakened) by other items in the display. There is no mechanism to direct resources to task-relevant stimuli; resources are simply depleted by virtue of being spread among too many stimuli. On the other hand, the concept of a *directed* resource is central to perceptual load theory. According to Lavie, high perceptual load tasks "engage full capacity" leaving "no capacity" for task-irrelevant material, whereas low perceptual load tasks fail to exhaust capacity leaving "spare capacity" that "spills over" onto task-irrelevant material (Lavie, 2010, p. 143). In other words, the distinction between task-relevant and task-irrelevant material is critical in determining the extent to which distractors are processed, because this distinction determines the extent to which task-relevant material fully engages a limited processing capacity. This is very similar to our concept of a bias. For us, competition is biased in favor of task-relevant material; ultimately the target item. As in perceptual load theory, this enhancement of task-relevant material occurs at the cost of task-irrelevant material. Unlike perceptual load theory, however, the cost is incurred due to the competitive interactions among elements in the display rather than a depletion of some unspecified "capacity." We note also that, for us, these competitive interactions occur in visual cortex; that is, the enhancement of the target in visual cortex, by virtue of the inhibitory interactions there, results in a suppression of the other stimuli including the distractor. Perceptual load theory, in contrast, appears to place the source of this capacity, and thus its depletion, in frontoparietal cortex (Lavie and Robertson, 2001; Kelley and Lavie, 2010), although it does acknowledge the interaction between frontoparietal and visual cortices (Remington et al., 2012). In our view, localizing the ultimate source of the competition in visual cortex is more in line with the characterization of this form of load as *perceptual.* As we have already noted, other cognitive capacity limitations, which may play a role in *cognitive* load (De Fockert et al., 2001; Kelley and Lavie, 2010; Lavie, 2010; Carmel et al., 2012), may result from here-to-now unknown competitive interactions among frontoparietal mechanisms.

The need for a strong bias to process high load displays can also explain why "high load" displays that are physically identical to low load displays (Lavie, 1995) can still produce little distractor processing, a set of results that cannot be explained by dilution theory. Such tasks manipulate perceptual load by varying task requirements rather than changing stimuli. For instance, participants are required to detect a conjunction target rather than a target defined by a single feature (Lavie, 1995; Handy and Mangun, 2000; Schwartz et al., 2005; Parks et al., 2011). These conditions require a top-down bias to bind the features together in a conjunction task (Duncan et al., 1997), again resulting in a suppression of the non-targets. In other words, a conjunction search requires a focused selection of the target whereas in feature search the target can be located without engaging a filter, or by leaving the attentional window open.

What is the evidence, first that a bias exists and, second that it enhances the target items at the expense of the task-irrelevant information? There is a large body of evidence showing that when the perceptual load of a task increases it engages frontoparietal mechanisms more strongly (Culham et al., 2001; Pinsk et al., 2004; Schwartz et al., 2005; Scalf and Beck, 2010; Shim et al., 2010; Gillebert et al., 2012; Ohta et al., 2012). Moreover, as proposed by load theory, the fact that a concurrent cognitive task (i.e., higher cognitive load) increases distractor processing presumably reflects the fact that both the selection mechanisms and the concurrent cognitive task draw on the same frontoparietal mechanisms (De Fockert et al., 2001; Lavie et al., 2004; Lavie, 2005, 2010). We add that our view that high load displays require a top-down bias also explains why increasing cognitive load not only increases distractor processing when the perceptual load of the display is low, as proposed by load theory, but also when it is high (Lavie et al., 2004). Top-down frontoparietal mechanisms would be needed in low load to prevent the participant from responding to the well-processed distractor (Lavie, 2005, 2010), but they would also be needed to resolve the target when the perceptual load is high. Thus, any concurrent task that draws on the same frontoparietal mechanisms would increase distractor processing in both cases.

Not only has frontoparietal activity been shown to increase with load, increases in activity in posterior parietal cortex and the frontal eye fields have also been shown to modulate activity in visual cortex (Moore and Armstrong, 2003; Ruff et al., 2006, 2008; Thut et al., 2006; Scalf and Beck, 2010; Scalf et al., 2011a; for review Noudoost et al., 2010). These data are all in keeping with a biased competition model in which attentional control regions in frontoparietal cortex bias activity in visual cortex in favor of an attended stimulus (Desimone and Duncan, 1995; Beck and Kastner, 2009). As already noted, the idea that enhancement of a target occurs at the expense of other stimuli in the display is fundamental to the principles of competitive interactions. If one stimulus is "pushed up" by attention then, by virtue of their competitive/inhibitory connections, other competing stimuli will necessarily be "pulled down." There are now also numerous neuroimaging studies that find such a push-pull relationship between target and distractor (Somers et al., 1999; Pinsk et al., 2004; Gazzaley et al., 2005; Pestilli and Carrasco, 2005; Hopf et al., 2006). More importantly, the extent of this push-pull relationship (i.e., the difference between activity evoked by task-relevant and task-irrelevant stimuli) is modulated by the perceptual load of the relevant task (Handy et al., 2001; Schwartz et al., 2005; Parks et al., 2011).

HOW TO DEFINE "LOW LOAD"

Why, according to our biased competition framework of distractor processing, do Tsal and Benoni's "high dilution/low load" displays produce such small distractor effects? Like Lavie, Tsal and Benoni define low load tasks as those that are performed quickly and accurately. According to a biased competition framework, however, it is not the speed with which participants can perform the task that is important, but whether or not a top-down bias is needed to identify the target. The question then becomes whether, under their various "low load" manipulations (Benoni and Tsal, 2010, 2012; Tsal and Benoni, 2010), the representation of the target is clear in visual cortex without further enhancement by selective attention. We believe that if the representation is clear, the attentional window is left open; no bias is then needed to selectively enhance the target at the expense of the distractors, allowing the distractor to be more fully processed. Consistent with this view, Roper et al. (2013) recently showed that the size of the flanker effect increased with increasing search efficiency; that is, those targets that were most likely to be detected in parallel (or with the least amount of serial search) were the most affected by the compatibility of distractors.

We note that implicit in our view of load is the idea that the application of the bias is effortful, and therefore will not occur if the participant can quickly acquire the target without it. This, in a sense, explains why processing of the distractor under low load is, in Lavie's language, obligatory (Lavie, 2005, 2010). Although excluding the distractor may be optimal (i.e., applying a bias even in low load displays), participants are unable or unwilling to do so if the target can be acquired quickly without the bias; after all, participants' primary task is to simply report the target as quickly and as accurately as possible.

What is unclear in Tsal and Benoni's "high dilution/low load" displays is whether or not their "low load" displays actually negate the need for a top-down bias. If they do not, then in our view, they are not "low load" displays. Only if the target is already clearly represented in visual cortex without attention, and thus requires no bias to be identified, would we predict a "low load" processing mode; that is, an open attentional window with no filter. Determining whether Tsal and Benoni's targets are resolved in visual cortex without top-down attention requires knowing how visual cortex responds to their displays under conditions in which the participants' attention is directed elsewhere. For example, we have shown that competition is reduced in visual cortex when the display contains a stimulus that differed in orientation and color from an otherwise homogenous set of stimuli (Beck and Kastner, 2005). This reduction in competition for pop-out displays (relative to a fully heterogeneous stimulus display) was apparent even in V1, and occurred despite the fact that the stimuli were task-irrelevant and subjects were engaged in a demanding central letter detection task. The very early effect of a pop-out stimulus is consistent with single-cell recordings indicating that V1 is sensitive to local feature contrast, specifically when the stimulus differs from a homogenous surround (Knierim and Van Essen, 1992; Kastner et al., 1997, 1999; Nothdurft et al., 1999).

Critically, however, Tsal and Benoni do not use homogenous non-targets and thus our pop-out data do not apply; the presence of heterogeneous letters is what makes their displays high dilution. Instead they use color or position to cue the participant to the target, which speeds RTs and improves accuracy. Are such manipulations sufficient to improve the clarity of the target without attention though? Certainly these manipulations provide cues to guide top-down attention. Participants can use color or relative position to find the target, but if the participants are "using" this information, they may be doing so through a spatially specific top-down bias. Consistent with the idea that subjects are applying a bias, RTs to find the target in the "high dilution/low load" displays of Tsal and Benoni tend to be higher than in the classic low load displays (Benoni and Tsal, 2010, 2012; Tsal and Benoni, 2010).

Of course, color information could, in theory, be used segregate the target in a bottom-up manner. For instance, a unique color might be sufficient to segregate the color singleton from the other letters as early as V1 (Zipser et al., 1996; Li, 1999, 2002), but the question is whether V1 represents the form of the letter sufficiently to support its identification when that letter is surrounded by other letters, even if those letters are of a different color. In other words, it is one thing to say that color makes the target salient in visual cortex, but it is another to say that its form is then necessarily resolvable without attention. As far as we know, this has not been directly assessed in visual cortex.

CONCLUSIONS

We propose a neurally plausible explanation of limited resources in terms of competition for representation. This explanation has consequences for perceptual load and dilution theories. In particular, our biased competition interpretation of the data shares concepts with both theories. The competition component of our explanation is similar to the concept of dilution, the only difference being that the former proposes a specific mechanism for limited capacity behavior whereas the latter relies on the notion of a limited capacity resource. These concepts are easily reconciled, however, if one simply considers competition for representation as the underlying cause of dilution. Our biased competition explanation also shares an important feature with perceptual load theory. Competition can be biased in favor of an item; we argue that this is necessary in high load displays in order to evoke a representation whose resolution is fine enough to support its identification. Importantly then, like perceptual load theory, biased competition theory predicts that "resources" are directed toward the target at the expense of the non-targets and distractors. Dilution theory, in contrast, provides no such distinction.

In short, because our biased competition framework incorporates aspects of both dilution and perceptual load, we see it as a hybrid of both theories that incorporates known neural mechanisms. We believe dilution occurs and is responsible in part for the presence or absence of distractor processing. We also believe, however, that this cannot be the full explanation of the "perceptual load effect." Instead, a mechanism for directing attention and filtering out task-irrelevant stimuli must also play a role in distractor processing.

Finally, although our explanation shares similarities with both perceptual load and dilution theories, we see it as an improvement on both because it draws on known neural mechanisms and provides a neurally plausible alternative to the concept of a fixed capacity resource. Admittedly, the notion of a capacity or resource provides an intuitive metaphor with considerable predictive validity for explaining limited capacity behavior; it is unlikely, however, to be accurate at a neural level. In our view, the actual implementation of the "limited capacity" more likely reflects the interplay of competition for representation and top-down biases invoked to resolve the competition in favor of the target.

REFERENCES

Alvarez, G. A., and Cavanagh, P. (2005). Independent resources for attentional tracking in the left and right visual hemifields. *Psychol. Sci.* 16, 637–643.

Alvarez, G. A., and Franconeri, S. L. (2007). How many objects can you track? Evidence for a resource-limited attentive tracking mechanism. *J. Vis.* 7, 14.1–14.10.

Alvarez, G. A., Gill, J., and Cavanagh, P. (2012). Anatomical constraints on attention: hemifield independence is a signature of multifocal spatial selection. *J. Vis.* 12:9. doi: 10.1167/12.5.9

Bahcall, D. O., and Kowler, E. (1999). Attentional interference at small spatial separations. *Vision Res.* 39, 71–86.

Bahrami, B., Lavie, N., and Rees, G. (2007). Attentional load modulates responses of human primary visual cortex to invisible stimuli. *Curr. Biol.* 17, 509–513.

Bays, P. M., Wu, E. Y., and Husain, M. (2011). Storage and binding of object features in visual working memory. *Neuropsychologia* 49, 1622–1631.

Beck, D., and Lavie, N. (2005). Look here but ignore what you see: effects of distractors at fixation. *J. Exp. Psychol. Hum. Percept. Perform.* 31, 592–607.

Beck, D. M., and Kastner, S. (2005). Stimulus context modulates competition in human extrastriate cortex. *Nat. Neurosci.* 8, 1110–1116.

Beck, D. M., and Kastner, S. (2007). Stimulus similarity modulates competitive interactions in human visual cortex. *J. Vis.* 7, 19.1–19.12.

Beck, D. M., and Kastner, S. (2009). Top-down and bottom-up mechanisms in biasing competition in the human brain. *Vision Res.* 49, 1154–1165.

Benoni, H., and Tsal, Y. (2010). Where have we gone wrong? Perceptual load does not affect selective attention. *Vision Res.* 50, 1292–1298.

Benoni, H., and Tsal, Y. (2012). Controlling for dilution while manipulating load: perceptual and sensory limitations are just two aspects of task difficulty. *Psychon. Bull. Rev.* 19, 631–638.

Blakemore, C., and Tobin, E. A. (1972). Lateral inhibition between orientation detectors in the cat's visual cortex. *Exp. Brain Res.* 15, 439–440.

Bles, M., Schwarzbach, J., De Weerd, P., Goebel, R., and Jansma, B. M. (2006). Receptive field size-dependent attention effects in simultaneously presented stimulus displays. *Neuroimage* 30, 506–511.

Broadbent, D. E. (1958). *Perception and Communication*. London: Pergamon.

Carlson, T. A., Alvarez, G. A., and Cavanagh, P. (2007). Quadrantic deficit reveals anatomical constraints on selection. *Proc. Natl. Acad. Sci. U.S.A.* 104, 13496–13500.

Carmel, D., Fairnie, J., and Lavie, N. (2012). Weight and see: loading working memory improves incidental identification of irrelevant faces. *Front. Psychol.* 3:286. doi: 10.3389/fpsyg.2012.00286

Cartwright-Finch, U., and Lavie, N. (2007). The role of perceptual load in inattentional blindness. *Cognition* 102, 321–340.

Chelazzi, L., Duncan, J., Miller, E. K., and Desimone, R. (1998). Responses of neurons in inferior temporal cortex during memory-guided visual search. *J. Neurophysiol.* 80, 2918–2940.

Chelazzi, L., Miller, E. K., Duncan, J., and Desimone, R. (2001). Responses of neurons in macaque area V4 during memory-guided visual search. *Cereb. Cortex* 11, 761–772.

Cherry, E. C. (1953). Some experiments on the recognition of speech with one and with two ears. *J. Acoust. Soc. Am.* 25, 975–979.

Cisek, P. (2006). Integrated neural processes for defining potential actions and deciding between them: a computational model. *J. Neurosci.* 26, 9761–9770.

Cisek, P. (2007). Cortical mechanisms of action selection: the affordance competition hypothesis. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* 362, 1585–1599.

Cisek, P. (2012). Making decisions through a distributed consensus. *Curr. Opin. Neurobiol.* 22, 927–936.

Cohen, A., and Ivry, R. B. (1991). Density effects in conjunction search: evidence for a coarse location mechanism of feature integration. *J. Exp. Psychol. Hum. Percept. Perform.* 17, 891–901.

Culham, J., Cavanagh, P., and Kanwisher, N. (2001). Attention response functions: characterizing brain areas using fMRI activation during parametric variations of attentional load. *Neuron* 32, 737–745.

DeAngelis, G. C., Robson, J. G., Ohzawa, I., and Freeman, R. D. (1992). Organization of suppression in receptive fields of neurons in cat visual cortex. *J. Neurophysiol.* 68, 144–163.

De Fockert, J., Rees, G. E., Frith, C., and Lavie, N. (2001). The role of working memory in visual selective attention. *Science* 291, 1803–1806.

De Haan, B., Karnath, H.-O., and Driver, J. (2012). Mechanisms and anatomy of unilateral extinction after brain injury. *Neuropsychologia* 50, 1045–1053.

Delvenne, J. F. (2005). The capacity of visual short-term memory within and between hemifields. *Cognition* 96, B79–B88.

Desimone, R., and Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annu. Rev. Neurosci.* 18, 193–222.

Duncan, J., Humphreys, G., and Ward, R. (1997). Competitive brain activity in visual attention. *Curr. Opin. Neurobiol.* 7, 255–261.

Dux, P. E., Ivanoff, J., Asplund, C. L., and Marois, R. (2006). Isolation of a central bottleneck of information processing with time-resolved FMRI. *Neuron* 52, 1109–1120.

Epstein, R., and Kanwisher, N. (1998). A cortical representation of the local visual environment. *Nature* 392, 598–601.

Erickson, K. I., Colcombe, S. J., Wadhwa, R., Bherer, L., Peterson, M., Scalf, P. E., et al. (2007). Training-induced functional activation changes in dual-task processing: an fMRI study. *Cereb. Cortex* 17, 192–204.

Eriksen, B. A., and Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target in a non-search task. *Percept. Psychophys.* 16, 143–149.

Eriksen, C. W., and St. James, J. D. (1986). Visual attention within and around the field of focal attention: a zoom lens model. *Percept. Psychophys.* 40, 225–240.

Forster, S., and Lavie, N. (2008). Failures to ignore entirely irrelevant distractors: the role of load. *J. Exp. Psychol. Appl.* 14, 73–83.

Franconeri, S. L., Alvarez, G. A., and Cavanagh, P. (2013). Flexible cognitive resources: competitive content maps for attention and memory. *Trends Cogn. Sci.* 17, 134–141.

Franconeri, S. L., Jonathan, S. V., and Scimeca, J. M. (2010). Tracking multiple objects is limited only by object spacing, not by speed, time, or capacity. *Psychol. Sci.* 21, 920–925.

Franconeri, S. L., Alvarez, G. A., and Enns, J. T. (2007). How many locations can be selected at once? *J. Exp. Psychol. Hum. Percept. Perform.* 33, 1003–1012.

Gattass, R., Sousa, A. P., and Gross, C. G. (1988). Visuotopic organization and extent of V3 and V4 of the macaque. *J. Neurosci.* 8, 1831–1845.

Gazzaley, A., Cooney, J. W., McEvoy, K., Knight, R. T., and D'Esposito, M. (2005). Top-down enhancement and suppression of the magnitude and speed of neural activity. *J. Cogn. Neurosci.* 17, 507–517.

Gillebert, C. R., Dyrholm, M., Vangkilde, S., Kyllingsbaek, S., Peeters, R., and Vandenberghe, R. (2012). Attentional priorities and access to short-term memory: parietal interactions. *Neuroimage* 62, 1551–1562.

Handy, T. C., and Mangun, G. R. (2000). Attention and spatial selection: electrophysiological evidence for modulation by perceptual load. *Percept. Psychophys.* 62, 175–186.

Handy, T. C., Soltani, M., and Mangun, G. R. (2001). Perceptual load and visuocortical processing: ERP evidence for sensory-level selection. *Psychol. Sci.*12, 213–218.

Hilimire, M. R., Mounts, J. R. W., Parks, N. A., and Corballis, P. M. (2010). Event-related potentials dissociate effects of salience and space in biased competition for visual representation. *PLoS ONE* 5:e12677. doi: 10.1371/journal.pone.0012677

Hopf, J. M., Boehler, C. N., Luck, S. J., Tsotsos, J. K., Heinze, H. J., and Schoenfeld, M. A. (2006). Direct neurophysiological evidence for spatial suppression surrounding the focus of attention in vision. *Proc. Natl. Acad. Sci. U.S.A.* 103, 1053–1058.

Intriligator, J., and Cavanagh, P. (2001). The spatial resolution of visual attention. *Cogn. Psychol.* 43, 171–216.

James, W. (1890). *The Principles of Psychology.* New York, NY: Holt.

Jersild, A. T. (1927). Mental set and shift. *Arch. Psychol.* 89, 5–82.

Kahneman, D. (1973). *Attention and Effort.* Englewood Cliffs, NJ: Prentice-Hall.

Kanwisher, N., McDermott, J., and Chun, M. M. (1997). The fusiform face area: a module in human extrastriate cortex specialized for face perception. *J. Neurosci.* 17, 4302–4311.

Kastner, S., De Weerd, P., Desimone, R., and Ungerleider, L. G. (1998). Mechanisms of directed attention in the human extrastriate cortex as revealed by functional MRI. *Science* 282, 108–111.

Kastner, S., De Weerd, P., Pinsk, M. A., Elizondo, M. I., Desimone, R., and Ungerleider, L. G. (2001). Modulation of sensory suppression: implications for receptive field sizes in the human visual cortex. *J. Neurophysiol.* 86, 1398–1411.

Kastner, S., Nothdurft, H. C., and Pigarev, I. (1997). Neuronal correlates of pop-out in cat striate cortex. *Vision Res.* 37, 371–376.

Kastner, S., Nothdurft, H. C., and Pigarev, I. (1999). Neuronal responses to motion and orientation contrast in cat striate cortex. *Vis. Neurosci.* 16, 587–600.

Kelley, T. A., and Lavie, N. (2010). Working memory load modulates distractor competition in primary visual cortex. *Cereb. Cortex* 21, 659–665.

Knierim, J. J., and Van Essen, D. C. (1992). Neuronal responses to static texture patterns in area V1 of the alert macaque monkey. *J. Neurophysiol.* 67, 961–980.

Kramer, A. F., Coyne, J. T., and Strayer, D. L. (1993). Cognitive function at high altitude. *Hum. Factors* 35, 329–344.

Kristjánsson, Á., and Nakayama, K. (2002). The attentional blink in space and time. *Vision Res.* 42, 2039–2050.

Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. *J. Exp. Psychol. Hum. Percept. Perform.* 21, 451–468.

Lavie, N. (2005). Distracted and confused?: selective attention under load. *Trends Cogn. Sci.* 9, 75–82.

Lavie, N. (2006). The role of perceptual load in visual awareness. *Brain Res.* 1080, 91–100.

Lavie, N. (2010). Attention, distraction, and cognitive control under load. *Curr. Dir. Psychol. Sci.* 19, 143–148.

Lavie, N., and Cox, S. (1997). On the efficiency of visual selective attention: efficient visual search leads to inefficient distractor rejection. *Psychol. Sci.* 8, 395–398.

Lavie, N., Hirst, A., De Fockert, J. W., and Viding, E. (2004). Load theory of selective attention and cognitive control. *J. Exp. Psychol. Gen.* 133, 339–354.

Lavie, N., and Robertson, I. (2001). The role of perceptual load in visual neglect: rejection of ipsilesional distractors is facilitated with higher central load. *J. Cogn. Neurosci.* 13, 867–876.

Lavie, N., and Tsal, Y. (1994). Perceptual load as a major determinant of the locus of selection in visual attention. *Percept. Psychophys.* 56, 183–197.

Li, Z. (1999). Contextual influences in V1 as a basis for pop out and asymmetry in visual search. *Proc. Natl. Acad. Sci. U.S.A.* 96, 10530–10535.

Li, Z. P. (2002). A saliency map in primary visual cortex. *Trends Cogn. Sci.* 6, 9–16.

Luck, S. J., Hillyard, S. A., Mangun, G. R., and Gazzaniga, M. S. (1989). Independent hemispheric attentional systems mediate visual search in split-brain patients. *Nature* 342, 543–545.

Luck, S. J., Chelazzi, L., Hillyard, S. A., and Desimone, R. (1997). Neural mechanisms of spatial selective attention in areas V1, V2, and V4 of macaque visual cortex. *J. Neurophysiol.* 77, 24–42.

Macdonald, J. S. P., and Lavie, N. (2008). Load induced blindness. *J. Exp. Psychol. Hum. Percept. Perform.* 34, 1078–1091.

Malach, R., Reppas, J. B., Benson, R. R., Kwong, K. K., Jiang, H., Kennedy, W. A., et al. (1995). Object-related activity revealed by functional magnetic resonance imaging in human occipital cortex. *Proc. Natl. Acad. Sci. U.S.A.* 92, 8135–8139.

McCarley, J. S., Mounts, J. R. W., and Kramer, A. F. (2004). Age-related differences in localized attentional interference. *Psychol. Aging* 19, 203–210.

McCarley, J. S., Mounts, J. R. W., and Kramer, A. F. (2007). Spatially mediated capacity limits in attentive visual perception. *Acta Psychol.* 126, 98–119.

Mecklinger, A., Weber, K., Gunter, T. C., and Engle, R. W. (2003). Dissociable brain mechanisms for inhibitory control: effects of interference content and working memory capacity. *Brain Res.* 18, 26–38.

Mitchell, D. J., and Cusack, R. (2008). Flexible, capacity-limited activity of posterior parietal cortex in perceptual as well as visual short-term memory tasks. *Cereb. Cortex* 18, 1788–1798.

Moore, T., and Armstrong, K. M. (2003). Selective gating of visual signals by microstimulation of frontal cortex. *Nature* 421, 370–373.

Moran, J., and Desimone, R. (1985). Selective attention gates visual processing in the extrastriate cortex. *Science* 229, 782–784.

Mounts, J. R. W., and Gavett, B. E. (2004). The role of salience in localized attentional interference. *Vision Res.* 44, 1575–1588.

Mozer, M. C., and Sitton, M. (1998). Computational modeling of spatial attention. *Attention* 9, 341–393.

Nothdurft, H. C., Gallant, J. L., and Van Essen, D. C. (1999). Response modulation by texture surround in primate area V1: correlates of 'popout' under anesthesia. *Vis. Neurosci.* 16, 15–34.

Noudoost, B., Chang, M. H., Steinmetz, N. A., and Moore, T. (2010). Top-down control of visual attention. *Curr. Opin. Neurobiol.* 20, 183–190.

Ohta, H., Yamada, T., Watanabe, H., Kanai, C., Tanaka, E., Ohno, T., et al. (2012). An fMRI study of reduced perceptual load-dependent modulation of task-irrelevant activity in adults with autism spectrum conditions. *Neuroimage* 61, 1176–1187.

Parks, N. A., Hilimire, M. R., and Corballis, P. M. (2011). Steady-state signatures of visual perceptual load, multimodal distractor filtering, and neural competition. *J. Cogn. Neurosci.* 23, 1113–1124.

Pashler, H. (1994). Dual-task interference in simple tasks: data and theory. *Psychol. Bull.* 116, 220–244.

Pelli, D. G. (2008). Crowding: a cortical constraint on object recognition. *Curr. Opin. Neurobiol.* 18, 445–451.

Pestilli, F., and Carrasco, M. (2005). Attention enhances contrast sensitivity at cued and impairs it at uncued locations. *Vision Res.* 45, 1867–1875.

Pinsk, M. A., Doniger, G. M., and Kastner, S. (2004). Push-pull mechanism of selective attention in human extrastriate cortex. *J. Neurophysiol.* 92, 622–629.

Pylyshyn, Z. W., and Storm, R. W. (1988). Tracking multiple independent targets: evidence for a parallel tracking mechanism. *Spat. Vis.* 3, 179–197.

Rafal, R., Ward, R., and Danziger, S. (2006). Selection for action and selection for awareness: evidence from hemispatial neglect. *Brain Res.* 1080, 2–8.

Raymond, J. E., Shapiro, K. L., and Arnell, K. M. (1992). Temporary suppression of visual processing in an RSVP task: an attentional blink? *J. Exp. Psychol. Hum. Percept. Perform.* 18, 849–860.

Recanzone, G. H., and Wurtz, R. H. (2000). Effects of attention on MT and MST neuronal activity during pursuit initiation. *J. Neurophysiol.* 83, 777–790.

Reddy, L., Kanwisher, N. G., and VanRullen, R. (2009). Attention and biased competition in multi-voxel object representations. *Proc. Natl. Acad. Sci. U.S.A.* 106, 21447–21452.

Reddy, L., and VanRullen, R. (2007). Spacing affects some but not all visual searches: implications for theories of attention and crowding. *J. Vis.* 7, 3.1–3.17.

Rees, G., Frith, C., and Lavie, N. (1997). Modulating irrelevant motion perception by varying attentional load in an unrelated task. *Science* 278, 1616–1619.

Remington, A. M., Swettenham, J. G., and Lavie, N. (2012). Lightening the load: perceptual load impairs visual detection in typical adults but not in autism. *J. Abnorm. Psychol.* 121, 544–551.

Reynolds, J. H., Chelazzi, L., and Desimone, R. (1999). Competitive mechanisms subserve attention in macaque areas V2 and V4. *J. Neurosci.* 19, 1736–1753.

Reynolds, J. H., and Heeger, D. J. (2009). The normalization model of attention. *Neuron* 61, 168–185.

Roper, Z. J. J., Cosman, J. D., and Vecera, S. P. (2013). Perceptual load corresponds with factors known to influence visual search. *J. Exp. Psychol. Hum. Percept. Perform.* doi: 10.1037/a0031616. [Epub ahead of print].

Ruff, C. C., Bestmann, S., Blankenburg, F., Bjoertomt, O., Josephs, O., Weiskopf, N., et al. (2008). Distinct causal influences of parietal and frontal brain regions on activity in human retinotopic visual cortex. *Cereb. Cortex* 18, 817–827.

Ruff, C. C., Blankenburg, F., Bjoertomt, O., Bestmann, S., Freeman, E., Haynes, J. D., et al. (2006). Concurrent TMS-fMRI and psychophysics reveal frontal influences on human retinotopic visual cortex. *Curr. Biol.* 16, 1479–1488.

Sagi, D., and Julez, B. (1985). Fast noninertial shifts of attention. *Spat. Vis.* 1, 141–149.

Scalf, P. E., Banich, M. T., Kramer, A. F., Narechania, K., and Simon, C. D. (2007). Double take: parallel processing by the cerebral hemispheres reduces attentional blink. *J. Exp. Psychol. Hum. Percept. Perform.* 33, 298–329.

Scalf, P. E., Basak, C., and Beck, D. M. (2011a). Attention does more than modulate suppressive interactions: attending to multiple items. *Exp. Brain Res.* 212, 293–304.

Scalf, P. E., Dux, P. E., and Marois, R. (2011b). Working memory encoding delays top-down attention to visual cortex. *J. Cogn. Neurosci.* 23, 2593–2604.

Scalf, P. E., and Beck, D. M. (2010). Competition in visual cortex impedes attention to multiple items. *J. Neurosci.* 30, 161–169.

Schwartz, S., Vuilleumier, P., Hutton, C., Maravita, A., Dolan, R. J., and Driver, J. (2005). Attentional load and sensory competition in human vision: modulation of fMRI responses by load at fixation during task-irrelevant stimulation in the peripheral visual field. *Cereb. Cortex* 15, 770–786.

Shapiro, K. L., and Miller, C. E. (2011). The role of biased competition in visual short-term memory. *Neuropsychologia* 49, 1506–1517.

Shim, W., Vickery, T., Alvarez, G. A., and Jiang, Y. (2010). The number of attentional foci and their precision are dissociated in the posterior parietal cortex. *Cereb. Cortex* 20, 1341–1349.

Shim, W. M., Alvarez, G. A., and Jiang, Y. V. (2008). Spatial separation between targets constrains maintenance of attention on multiple objects. *Psychon. Bull. Rev.* 15, 390–397.

Somers, D. C., Dale, A. M., Seiffert, A. E., and Tootell, R. B. H. (1999). Functional MRI reveals spatially specific attentional modulation in human primary visual cortex. *Proc. Natl. Acad. Sci. U.S.A.* 96, 1663–1668.

Spence, C., Parise, C., and Chen, Y. C. (2012). *The Colavita Visual Dominance Effect*. Available online at: http://www.ncbi.nlm.nih.gov/books/NBK92851/. (Accessed March 19, 2013).

Sperling, G. (1960). The information available in brief visual presentations. *Psychol. Monogr. Gen. Appl.* 74, 1–29.

Ståhle, L., Ståhle, E. L., Granström, E., Isaksson, S., Annas, P., and Sepp, H. (2011). Effects of sleep or food deprivation during civilian survival training on cognition, blood glucose and 3-OH-butyrate. *Wilderness Environ. Med.* 22, 202–210.

Stroop, J. R. (1935). Studies of interference in serial verbal reaction. *J. Exp. Psychol.* 18, 643–662.

Thut, G., Nietzel, A., Brandt, S. A., and Pascual-Leone, A. (2006). Alpha-band electroencephalographic activity over occipital cortex indexes visuospatial attention bias and predicts visual target detection. *J. Neurosci.* 26, 9494–9502.

Todd, J. J., and Marois, R. (2004). Capacity limit of visual short-term memory in human posterior parietal cortex. *Nature* 428, 751–754.

Torralbo, A., and Beck, D. M. (2008). Perceptual load-induced selection as a result of local competitive interactions in visual cortex. *Psychol. Sci.* 19, 1045–1050.

Treisman, A. (1960). Contextual cues in selective listening. *Q. J. Exp. Psychol.* 12, 242–248.

Tsal, Y., and Benoni, H. (2010). Diluting the burden of load: perceptual load effects are simply dilution effects. *J. Exp. Psychol. Hum. Percept. Perform.* 36, 1645–1656.

VanRullen, R., and Koch, C. (2003). Competition and selection during visual processing of natural scenes and objects. *J. Vis.* 3, 75–85.

Welford, A. T. (1957). Changing demands of modern work and control. *Nature* 179, 1058–1059.

West, G. L., Pun, C., Pratt, J., and Ferber, S. (2010). Capacity limits during perceptual encoding. *J. Vis.* 10, 14.1–14.12.

Wickens, C. D. (1984). "Processing resources in attention," in *Varieties of Attention,* eds R. Parasuraman and D. R. Davies (New York, NY: Academic Press), 63–102.

Wickens, C. D., Vidulich, M., and Sandry-Garza, D. (1984). Principles of S-C-R compatibility with spatial and verbal tasks: the role of display-control location and voice-interactive display-control interfacing. *Hum. Factors* 26, 533–543.

Wilson, D. E., Muroi, M., and MacLeod, C. M. (2011). Dilution, not load, affects distractor processing. *J. Exp. Psychol. Hum. Percept. Perform.* 37, 319–335.

Xu, Y., and Chun, M. M. (2009). Selecting and perceiving multiple objects. *Trends Cogn. Sci.* 13, 167–174.

Zipser, K., Lamme, V. A., and Schiller, P. H. (1996). Contextual modulation in primary visual cortex. *J. Neurosci.* 16, 7376–7389.

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Beyond perceptual load and dilution: a review of the role of working memory in selective attention

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The perceptual load and dilution models differ fundamentally in terms of the proposed mechanism underlying variation in distractibility during different perceptual conditions. However, both models predict that distracting information can be processed beyond perceptual processing under certain conditions, a prediction that is well-supported by the literature. Load theory proposes that in such cases, where perceptual task aspects do not allow for sufficient attentional selectivity, the maintenance of task-relevant processing depends on cognitive control mechanisms, including working memory. The key prediction is that working memory plays a role in keeping clear processing priorities in the face of potential distraction, and the evidence reviewed and evaluated in a meta-analysis here supports this claim, by showing that the processing of distracting information tends to be enhanced when load on a concurrent task of working memory is high. Low working memory capacity is similarly associated with greater distractor processing in selective attention, again suggesting that the unavailability of working memory during selective attention leads to an increase in distractibility. Together, these findings suggest that selective attention against distractors that are processed beyond perception depends on the availability of working memory. Possible mechanisms for the effects of working memory on selective attention are discussed.

Keywords: selective attention, distractibility, working memory load, working memory capacity, review, meta-analysis

INTRODUCTION

The question of when visual selection takes place during information processing has been a major issue in selective attention research that long remained unresolved, given evidence for both early and late selection. Early selection is suggested by the finding, among others, of no evidence for identification of unattended information (e.g., Lachter et al., 2004). Conversely, peripheral irrelevant distractor letters tend to interfere with the identification of central target letters, suggesting that the distractors were processed at least to the level of letter identity (e.g., Eriksen and Eriksen, 1974). This implies late selection. Perceptual load theory (Lavie and Tsal, 1994; Lavie, 1995) offered a resolution to the debate, by suggesting that the locus of selection was dependent on the perceptual processing demands of the task at hand: high perceptual demands would prevent any distracting information to be processed, leading to early selection, whereas low perceptual demands would allow for the processing of distractors, necessitating late selection.

Studies directly investigating the effect of perceptual load long seemed to support the idea that the relevant perceptual processing demands determine the extent of processing for irrelevant information (e.g., Lavie, 1995; Lavie and Cox, 1997; Lavie et al., 2004). Recently, however, a rival explanation has been put forward, suggesting that the reduction in distractibility under high perceptual load is due to greater dilution of the distractor (Benoni and Tsal, 2010, 2012; Tsal and Benoni, 2010; Wilson et al., 2011). On this view, the high perceptual load conditions are associated with reduced distractibility simply because the distractors compete with the additional relevant non-targets in high load displays, rather than exhaustion of attentional capacity under high perceptual load.

The main difference between the load and dilution models concerns the mechanisms underlying perceptual selectivity, whereas both models assume that distractors are more likely to be processed under certain perceptual conditions. In such cases of relatively extensive distractor processing, behavior nonetheless remains largely goal-appropriate. In other words, although the processing of the perceived distractors under low perceptual load or low dilution has a measurable effect on target processing, observers are still able to prioritize target processing, and prevent for example responding inappropriately to distracting information. A key question therefore is: how are processing priorities maintained in order to achieve target-directed behavior when current perceptual aspects do not allow for sufficient attentional selectivity and distractors are likely to receive considerable processing?

Dilution involves a process of early selection: whether or not a distractor receives processing depends on perceptual characteristics of the visual display. As such, the dilution model makes no specific predictions regarding the fate of distracting information that has not been excluded from processing by dilution. Tsal and Benoni (2010) do offer an interpretation of load theory, suggesting that any additional increase in the load on attentional resources should reduce the likelihood that attentional resources spill over to the distractors. On this view, an increase in attentional load, even when it does not affect perceptual task aspects, should be associated with reduced distractor processing. As we outline below, this is not the case, and increases in attentional load that involve top-down attentional control, rather than stimulus-determined selection processes such as perceptual load, tend to have the effect of enhancing distractor processing.

Load theory suggests that cognitive control functions supported by the frontal lobes, particularly working memory, are critical in late selection (Lavie et al., 2004; Lavie, 2010). On this view, working memory plays a key role in maintaining processing priorities, so that target and distractor-related information remains clearly separated in processing, and behavior can be successfully directed toward task-relevant information. This idea was not new, and an earlier suggestion that working memory and selective attention may show functional overlap came in the context of Baddeley's working memory model (Baddeley, 1996), which argued that a key function of the central executive component of working memory is to facilitate selective attention to relevant information in the presence of potential distractions. At the time, the evidence for an association between working memory and selective attention was indirect and came from two lines of investigation. First, studies on age-related changes in selective attention had shown that the ability to prevent distraction by irrelevant information is disproportionately affected by age (e.g., Rabbitt, 1965; Hasher and Zacks, 1988). Together with the finding that working memory performance also deteriorates with age (e.g., Welford, 1958; Morris et al., 1988), this provided indirect evidence that working memory may somehow be involved in achieving selective processing. A second early suggestion that working memory may be involved in selective attention was made by Desimone and Duncan (1995), who argued that control of attention from the top down (i.e., not entirely based on attention-grabbing properties of the input), involves maintenance of a template specifying what information is relevant for the task at hand, a function ideally suited to working memory.

The first study to provide direct evidence for a role of working memory in selective attention used a paradigm combining a working memory task with a selective attention task to measure distractor interference in a context of varying working memory load (De Fockert et al., 2001). In that study, people performed a target name classification task (popstar, politician) while ignoring distractor faces (Young et al., 1986), so that any processing of the irrelevant faces would lead to poorer performance on trials on which the face category was incompatible with the current target name category (e.g., the name Elton John accompanied by the face of Bill Clinton), compared with trials on which the name and face categories were either compatible (e.g., the name and face of Elton John) or unrelated (e.g., the name Elton John with an anonymous face). The selective attention task was performed in a context of either low or high working memory load. At the start of each trial, people saw a set of five digits that they had to remember until the end of the trial in order to be able to respond to a memory probe. Working memory load was manipulated by varying the order of the set digits: on low load trials, digits always appeared in a sequential order, whereas a different random order was used on high load trials. The prediction was that, if working memory is important for maintaining selective attention to the relevant target names, then making it relatively unavailable to do so (by involving working memory in an additional task of high load) should lead to less selective processing. The results supported this prediction. Compatibility effects in terms of reaction times and accuracy rates were greater under high working memory load (78 ms difference between compatible and incompatible displays), compared to low load (46 ms difference). Moreover, the neural response in brain areas dedicated to processing the irrelevant faces was also greater under high (vs. low) working memory load. Following the initial indirect suggestions for a role of working memory in selective attention (Desimone and Duncan, 1995; Baddeley, 1996), this provided the first strong evidence that within the same participants, and without changing any properties of the selective attention task, working memory can be shown to affect visual distractibility.

The initial demonstration of a role of working memory in selective attention has prompted much further work on the association between these constructs. The main aim of this paper is to provide an overview of the evidence so far, focusing on the question of how the availability of working memory affects distractibility in selective attention. Other important aspects regarding the relation between working memory and selective attention, including how attention determines which information is entered into, and prioritized within, working memory (e.g., Oberauer, 2003; Gazzaley and Nobre, 2012), and how attention can be biased toward the contents of working memory (Awh and Jonides, 2001; Soto et al., 2008; Olivers et al., 2011), are not covered here. Instead, we will focus specifically on studies that manipulate the level of working memory availability during attention, and measure distractibility as a function of either load on working memory, or working memory capacity. As we will see, the majority of studies indeed show that the unavailability of working memory for selective attention leads to an increase in distractibility, although we will also discuss evidence suggesting that loading working memory can result in a reduction in distractibility in certain circumstances. Finally, studies elucidating the mechanism of how working memory may affect selective attention are discussed.

WORKING MEMORY LOAD AND DISTRACTIBILITY

Since the first experimental report that high working memory load can lead to greater processing of irrelevant information, a number of studies have found similar effects. The load-related increase in the interference effect from irrelevant faces in the popstar/politician task has been replicated in two experiments (Pecchinenda and Heil, 2007, Experiments 1 and 2; but see Jongen and Jonkman, 2011, for an example in which working memory load increased face distraction, but not significantly so). In a standard Eriksen-type flanker task (Eriksen and Eriksen, 1974), in which attention needs to be selectively directed toward a target letter in the presence of a distracting flanker letter, the interference effect produced by the flanker (measured by comparing performance to displays in which the distractor is compatible vs. incompatible with the target) is significantly enhanced during concurrent retention of a memory set of six digits (vs. one digit) (Lavie et al., 2004, Experiment 1; De Fockert et al., 2010; Ahmed and De Fockert, 2012b). Adding a working memory task has a similar effect of increasing the processing of irrelevant flankers other than letters, such as left or right-pointing arrows (Pratt et al., 2011). Both the popstar/politician task and the flanker tasks produce Stroop-type interference effects, whereby to-be-ignored distractors (faces, flanker letters, or arrows) are task-relevant to the extent that they are associated with a possible response. Indeed, color word interference in a classic Stroop task is also greater when load on working memory is high (Stins et al., 2004). The distractors appear on every trial in these tasks, making their presence perfectly predictable. That high working memory load increases the extent to which such distractors are processed, suggests that working memory is involved in the active suppression of known distractors.

A similar effect of working memory load of increasing distractor processing has been shown for distractors that are not task-relevant, and whose presence is not perfectly predictable. In visual search tasks, the presence of a salient singleton distractor leads to a performance impairment that is usually interpreted to reflect the capture of attention by the distractor (see Theeuwes, 2010, for a review). For example, search for a shape target is slower when one of the non-target display items has a unique color, even though color is an irrelevant dimension throughout the experiment (Theeuwes, 1992). Such attentional capture effects are greater under high working memory load (Boot et al., 2005; Lavie and De Fockert, 2005, 2006, but see De Fockert and Theeuwes, 2012, for an example where high working memory load did not modulate capture effects), suggesting that working memory is involved in minimizing the distraction caused by the singleton colors. Indirectly, the interpretation that singleton capture involves cognitive control, possibly working memory, is further supported by neuroimaging findings showing that the magnitude of capture in behavior is negatively correlated with activity in left frontal cortex (De Fockert et al., 2004). In addition to actively minimizing the capturing effect of the singletons, working memory may also be involved in merely detecting their presence. Activity in right prefrontal cortex is correlated with the magnitude of behavioral capture, this time showing a positive association, and only when concurrent working memory load is high (De Fockert and Theeuwes, 2012). This suggests that working memory may also play a role in the detection of the potential distraction: activity in right prefrontal cortex was greater in participants who experienced relatively strong attentional capture, but only when working memory load was high and the distractor singleton present.

Other findings also support the notion that working memory load affects the extent to which distractors are processed, even when these are not directly associated with a task response. The Ebbinghaus (or Titchener) illusion is a visual size illusion in which the perceived size of a target circle is affected by the size of surrounding inducer circles, such that a target surrounded by large inducers has a smaller perceived size compared to a target surrounded by small inducers (e.g., Roberts et al., 2005). The magnitude of the Ebbinghaus illusion can be seen as an index of selective attention, in that greater processing of the task-irrelevant inducers should lead to more illusion. Indeed, individuals who show superior selective attention on a range of tasks also experience very little Ebbinghaus illusion (De Fockert et al., 2011; Caparos et al., 2012, 2013). When the Ebbinghaus illusion is measured during performance of a concurrent working memory task, observers experience more Ebbinghaus illusion when they are maintaining a large digit set in working memory, compared to a small set (De Fockert and Wu, 2009). The same manipulation of working memory load has also been shown to affect inattentional blindness. When observers perform a demanding perceptual task involving comparing the sizes of two centrally presented lines, the one-off occurrence of an unexpected additional visual stimulus often goes unnoticed (Rock et al., 1992; Mack and Rock, 1998). Such inattentional blindness, however, can be eliminated by high working memory load (De Fockert and Bremner, 2011), suggesting that the task-irrelevant critical stimulus is more likely to be perceived when working memory is unavailable to maintain attention on the relevant task. A similar effect of working memory load on the processing of an irrelevant stimulus that is entirely task-irrelevant was shown by Carmel et al. (2012), who found that an irrelevant face presented alongside a relevant name categorization task was more likely to be subsequently identified when concurrent working memory load was high. Interestingly, this effect of working memory load was not found when the distracting images were buildings, suggesting that ignoring distractors that are salient (like faces) may be especially reliant on the availability of working memory.

The evidence that working memory is involved in preventing processing for distractors that are not directly associated with any task-relevant response is important, as it suggests that the effect of working memory on selective attention occurs at the level of sensory processing, rather than response selection. The effects of working memory load on attentional capture, the Ebbinghaus illusion, and detection of the critical item in inattentional blindness are unlikely to reflect a greater tendency to activate an incorrect response code following processing of the distractor. The attentional capture task requires responding to the orientation (horizontal, vertical) of a line in a target shape, and the non-target shapes never contain horizontal or vertical lines. Instead, the distracting singleton is defined by its unique color, which is not a relevant dimension in the task. In the Ebbinghaus task, response profiles would be opposite to those observed if people would mistakenly respond to the size of the distractors. In the inattentional blindness task, the critical item occurs only once and is not associated with any task response. It is thus unlikely that working memory acts on selective attention by preventing activation of responses associated with the distractors. Instead, the increases under high working memory load of the attentional capture effect, the Ebbinghaus illusion, and detection rates in inattentional blindness, seem to result from greater perception of the distractors under high load. This conclusion is further supported by fMRI evidence that the effects of working memory on distractor processing can be seen as early as V1 in primary visual cortex (Kelley and Lavie, 2011).

In addition to studies showing that working memory load leads to greater distractor interference when stimuli for both tasks are presented visually, there is also evidence that distractor processing increases when the working memory and selective attention tasks involve different sensory modalities (Dalton et al., 2009a,b). High load on a working memory task involving sub-vocal rehearsal of visually presented digits, during a task that required attending to target sounds and ignoring distractor sounds, led to greater interference from the auditory distractors (Dalton et al., 2009a). The same effect of increasing distractor interference when maintaining a large visually presented digit set in working memory has been shown when attention has to be directed toward a tactile target while ignoring an irrelevant tactile distractor (Dalton et al., 2009b). Conversely however, the difference in cost on the processing of visual targets produced by either tactile or painful distractors is reduced following a moderate increase in visual working memory load (Legrain et al., 2011), a result that could be interpreted to show that working memory led to a reduction in the attention capturing effect of the painful distractors. This suggests that working memory is more involved in reducing interference from distractors in the same modality as the target, compared to from those in a modality other than the target modality. Further work is required to test this speculation, directly comparing interference from same (vs. different) modality distractors on target processing under varying levels of load.

Although there is now evidence from a range of experimental tasks and measures that the unavailability of working memory during selective attention can increase the processing of distractors, the growing body of work on the role of working memory in selective attention has also occasionally found that working memory load can have different effects on distactibility. High working memory load has repeatedly been shown to either increase or reduce distractibility, depending on whether the contents of the working memory task overlap with the processing of the target or the distractor in a selective attention task, respectively (Kim et al., 2005; Park et al., 2007; de Liaño et al., 2010). High working memory load involving maintaining a set of letters leads to greater processing of the irrelevant color of a Stroop color word when the meaning of the word has to be attended (and the color ignored), but to reduced processing of the irrelevant word when the color has to be attended (and word meaning ignored). High load on a working memory task for spatial location has no effect on distractor processing in either case (Kim et al., 2005; de Liaño et al., 2010). Similarly, when the working memory task involves memorizing either faces or houses, and the selective attention task also requires attending to faces and ignoring houses, or vice versa, distractor effects are increased when the working memory items are of the same category as the targets in the attention task, but reduced when they are the same as the distractors (Park et al., 2007). These findings imply that working memory can be loaded for a specific stimulus category, and that the loaded category has to overlap with target processing in order to lead to an increase in distractor processing. Other work also suggests that cognitive load can have opposite effects on distractibility depending on the nature of the distracting information. Boot et al. (2005) found that, whereas attentional capture by color singletons was increased under high cognitive load, capture by sudden onsets was reduced. As argued below, the salience of the distractor may be an important factor determining whether working memory load will affect distractor processing.

How does the notion that the contents of the working memory load need to overlap with target processing (Kim et al., 2005; Park et al., 2007) correspond with other evidence? In many studies showing an increase in distractibility under high working memory load, the load manipulation involved maintaining digit sets or digit order. This working memory task indeed sometimes overlapped with target processing on the selective attention task. When the selective attention task required attending to target names and ignoring distractor faces (De Fockert et al., 2001), the working memory task can be argued to have more in common with the verbal requirements of classifying the target names than with identifying the distractor faces. Other findings, however, do not correspond well with the claim that the type of working memory load has to show more overlap with target than with distractor processing in order to increase distractibility. Greater distractor processing has been observed when the working memory task overlaps equally with target and distractor processing, such as when both target and distractor are letters (Lavie et al., 2004) or arrows (Pratt et al., 2011). Moreover, working memory load for digits also increases distractor processing when the target task requires size judgments (De Fockert and Wu, 2009; De Fockert and Bremner, 2011), and even when the selective attention task involves a different modality to the working memory task (Dalton et al., 2009a,b). It seems that working memory load is capable of increasing distractibility even if the overlap between the contents of the working memory task and target processing in selective attention is minimal.

In our own work, we have also come across cases in which high working memory load did not produce an increase in the level of distractor processing. In a recent fMRI study, we found that the behavioral attentional capture effect was not enhanced by high working memory load, even though the response in inferior frontal gyrus showed a reliable interaction between working memory load and the presence of the distracting singleton (De Fockert and Theeuwes, 2012). In that study, conditions in which the color singleton was present or absent were blocked. It is possible that this reduced the salience of the distractors, as their presence was perfectly predictable, unlike in previous work that did show an effect of working memory load on attentional capture by color singletons, but in which trials on which the distractor singleton was present and absent either occurred randomly within a block (Lavie and De Fockert, 2005), or in which the singleton color could coincide with either the target or a distractor within a block (Boot et al., 2005). Other work has also shown that the processing of expected distractors is less likely to be affected by working memory load (Macdonald and Lavie, 2008). Additionally, as shown by Carmel et al. (2012), distractor processing is only affected by working memory load when the distractor is sufficiently salient (faces, rather than buildings in their study), although the influence of visual working memory load on Simon interference effects (produced by the irrelevant location of a target stimulus, arguably a particularly salient form of interference) is less clear (Stins et al., 2004), and emotional faces produce interference regardless of the level of concurrent working memory load (Pecchinenda and Heil, 2007, Experiment 3). Together, these findings suggest that distractor salience is an important factor affecting whether working memory load influences selective attention. Effects of working memory load on interference may show an inverted-U shaped function as distractor salience increases: non-salient distractors (e.g., buildings) can be ignored even when working memory is loaded, whereas highly salient distractors (e.g., emotional faces, the irrelevant target location in the Simon task, sudden onset singletons) are processed even when working memory is available. When the salience of the distractor falls between these extremes (e.g., faces, letters associated with a task response, color singletons), working memory is able to prevent distractor processing. Further work is needed to systematically investigate the role of distractor salience.

Distraction by deviant sounds has also been found to be reduced under high working memory load (Berti and Schröger, 2003; SanMiguel et al., 2008), although the increase in working memory load (from $n = 0$ to $n = 1$ on an n-back task) may have insufficiently loaded working memory to lead to an increase in distractibility in these studies. In another recent study, we found that high working memory load can lead to significantly reduced distractibility in the Navon task (Ahmed and De Fockert, 2012a). In the Navon task, global stimuli consist of many local elements, and attention has to be directed to either the global shape or the local elements (Navon, 1977). Distractibility can be measured by comparing performance in conditions in which information at the attended and unattended levels is compatible (vs. incompatible). When attention was directed to the local level, working memory load had the expected effect of increasing distractibility from the global level. Conversely however, distractor effects were reduced by high working memory load when attention was directed to the global level, and the local level had to be ignored. Below, we will discuss these findings further when we consider a possible mechanism of the effect of working memory load on attention.

To sum up the work using manipulations of working memory load during selective attention, there is much evidence that processing of task-irrelevant information is enhanced when load on a concurrent task of working memory is high, implying that working memory plays a role in the active control against distractor interference. The effect of working memory on selective attention has been demonstrated in Stroop-type tasks, where the distractor is associated with one of the task responses, but also in tasks in which the distractor cannot lead to response activation, suggesting that the effect of working memory has an early locus in attention. In contrast, there are also examples in which high working load has not led to an increase in the extent of distractor processing in selective attention. These include situations in which the content of the working memory task overlaps mostly with the processing of the distractor (rather than the target) in selective attention (e.g., Kim et al., 2005), although there are many studies in which high working memory load does lead to greater distractor processing despite minimal overlaps between the working memory task and target processing. Distractor processing may be more likely to increase under high working memory load when distractors are likely to cause interference, either because they are associated with a task-relevant response, or because they have an intermediate level of salience or occur unpredictably from trial to trial.

On balance, the evidence for greater distractor processing under high working memory load seems stronger than the evidence for the opposite effect. Indeed, a meta-analysis on the effect sizes reported in 26 studies (49 experiments) manipulating working memory load during selective attention shows that the prevailing effect of working memory load is to increase distractor processing [mean $r = 0.202$, $t_{(48)} = 2.95$, SEM $= 0.0686$, $p < 0.005$; see **Table 1**]. This is a strong finding, as it includes experiments that found reversed effects (reduced distractibility under load) that were nevertheless predicted on the basis of changes to the spatial profile of attention, and that also showed that high working memory load did increase distractor processing when expected to do so (see below; Ahmed and De Fockert, 2012a,b). In addition, there were significantly more demonstrations of increases in distractibility under high working memory load (35 experiments) than reductions [14 experiments; $\chi^2_{(1)} = 9.0$, $p < 0.01$, two-tailed], although the magnitude of the effect was the same in studies showing an increase (mean $r = 0.477$) and those showing a reduction (mean $r = 0.484$, $p > 0.9$). We note that any bias against publication of null results means that unreported failures to replicate the original effect are likely to exist, although such bias will not have affected the number of reported reliable reversals of the effect.

The finding that high working memory load is associated with increased distractor processing is in line with load theory of selective attention (Lavie et al., 2004). According to the model, active control against processing of perceived distractors requires the availability of working memory, in order to maintain a clear distinction between relevant and irrelevant processing. High load on a working memory task that has to be performed concurrently with a selective attention leaves less capacity available for the prioritization of relevant targets, leading to the greater distractibility found in the studies reviewed here.

INDIVIDUAL DIFFERENCES IN WORKING MEMORY CAPACITY AND DISTRACTIBILITY

The evidence discussed so far for a role of working memory in distractor processing has been based on manipulations of working memory load, usually within the same participants. A converging line of evidence for the claim that working memory is involved in the extent of distractor processing in selection comes from studies investigating selective attention in individuals with varying levels of working memory capacity. The rationale is that the availability of working memory for selective attention is chronically reduced in individuals with low working memory capacity, compared to those with higher capacity. Consequently, differences in distractibility between individuals with either low or high working memory capacity should be similar to differences in distractibility within the same the person under either high working or low working memory load, respectively.

There is much evidence that attention performance is associated with working memory capacity, often showing that individuals with greater working memory capacity are more efficient at focusing their attention to task-appropriate information (the "controlled attention theory of working memory," e.g., Engle et al., 1999; Conway et al., 2001; Kane and Engle, 2003; Engle and Kane, 2004). For example, when repeating an attended auditory message while ignoring a simultaneously presented irrelevant message, low working memory span individuals are three

Table 1 | Effect sizes (*r*) for the effect of working memory (WM) load (unless stated otherwise) on distractor processing (reaction time effects, unless stated otherwise).

Source	Experiment	Effect size (*r*)	Effect of working memory load on
De Fockert et al. (2001)		**0.773**	Interference from distractor faces
Berti and Schröger (2003)		**−0.644**	Distraction by auditory deviant
Lavie et al. (2004)	1	**0.604**	Interference from distractor letters (flanker interference)
Lavie et al. (2004)	2	**0.514**	Flanker interference with articulatory suppression
Lavie et al. (2004)	3	**0.667**	Flanker interference under low, high perceptual load
Lavie et al. (2004)	4	**0.752**	Flanker interference (single vs. dual task with high load)
Lavie et al. (2004)	5	**0.836**	Flanker interference (single vs. dual task with low load)
Stins et al. (2004)	1	**0.369**	Stroop interference (spatial WM task)
Stins et al. (2004)	2	**−0.440**	Simon congruence effect (spatial WM task)
Boot et al. (2005)	1	0.410	Attentional capture by onset singletons
Boot et al. (2005)	2	**0.414**	Attentional capture by color singletons
Lavie and De Fockert (2005)	1	**0.653**	Attentional capture by color singletons
Lavie and De Fockert (2005)	2	**0.642**	Attentional capture by color singletons
Kim et al. (2005)	1a	**0.658**	Stroop interference (verbal WM condition, target load)
Kim et al. (2005)	2a	**−0.638**	Stroop interference (verbal WM condition, distractor load)
Kim et al. (2005)	3a	**0.660**	L/R congruency (verbal WM condition, target load)
Kim et al. (2005)	3b	−0.548	L/R congruency (verbal WM condition, distractor load)
Park et al. (2007)	1	**0.335**	Interference on same/different judgments (target load)
Park et al. (2007)	1	**−0.299**	Interference on same/different judgments (distractor load)
Park et al. (2007)	2	**0.464**	Interference on same/different judgments (target load)
Park et al. (2007)	2	**−0.483**	Interference on same/different judgments (distractor load)
Chen and Chan (2007)	3	0.052	Flanker interference (narrow focus condition)
Pecchinenda and Heil (2007)	1	**0.447**	Interference from distractor faces
Pecchinenda and Heil (2007)	2	**0.426**	Interference from distractor faces
Pecchinenda and Heil (2007)	3	−0.062	Interference from emotional distractor faces
SanMiguel et al. (2008)		**−0.703**	Distraction by auditory deviant
Macdonald and Lavie (2008)	6	0.336	Detection of expected stimulus during letter search
Dalton et al. (2009a)		**0.443**	Interference from auditory distractors
Dalton et al. (2009b)	1	**0.505**	Interference from tactile distractors (accuracy rates)
Dalton et al. (2009b)	2	**0.455**	Interference from tactile distractors (accuracy rates)
De Fockert and Wu (2009)		**0.660**	Ebbinghaus illusion
Kelley and Lavie (2011)		**0.360**	Interference from distractor objects
de Liaño et al. (2010)	1	**−0.421**	Stroop interference (distractor load) (inverse efficiency scores)
De Fockert et al. (2010)	2	**0.453**	Flanker interference (prime display)
Jongen and Jonkman (2011)		0.013	Interference from distractor faces
Legrain et al. (2011)		**−0.768**	Capture by painful (vs. non-painful) tactile distractors
Pratt et al. (2011)		**0.567**	Interference from distractor arrows (accuracy rates)
De Fockert and Bremner (2011)	1	**0.483**	Target detection in inattentional blindness
De Fockert and Bremner (2011)	2	**0.421**	Target detection in inattentional blindness
De Fockert and Theeuwes (2012)		−0.465	Attentional capture by color singletons
Carmel et al. (2012)	1	**0.225**	Distractor face identification
Carmel et al. (2012)	2	**0.327**	Distractor face identification
Carmel et al. (2012)	3	0.096	Distractor house identification
Ahmed and De Fockert (2012a)	1	**0.613**	Navon interference from global level
Ahmed and De Fockert (2012a)	2	**−0.620**	Navon interference from local level
Ahmed and De Fockert (2012a)	3	**0.291**	Navon interference from global level
Ahmed and De Fockert (2012a)	3	**−0.261**	Navon interference from local level
Ahmed and De Fockert (2012b)	1	**0.763**	Flanker interference (High WM capacity)
Ahmed and De Fockert (2012b)	1	−0.422	Flanker interference (Low WM capacity)

Positive effect sizes represent cases where distractor processing was greater under high (vs. low) working memory load. Negative effect sizes represent cases where distractor processing was greater under low (vs. high) working memory load. Effect sizes in bold are statistically significant effects at $p < 0.05$. Papers included in the meta-analysis were first identified via PubMed (search terms "working memory selective attention"). The search returned 750 articles, from which relevant papers were selected, i.e., when they measured distractor processing in selective attention whilst manipulating working memory load. In addition, any relevant work was included that was cited in the selected papers, but had not been identified in the PubMed search.

times more likely than high span individuals to report hearing their own name in the irrelevant message (Conway et al., 2001). High working memory span individuals are also faster than those with lower span at identifying a target letter at an uncued location, implying better attentional control in the high span individuals (Kane et al., 2001). Performance in high span individuals, compared to low span individuals, is less affected by the presence of an unexpected auditory deviant and their ERPs also show a smaller N1 component associated with infrequent auditory stimuli, again suggesting they are better at preventing processing for the irrelevant distractors (Sörqvist et al., 2012; Tsuchida et al., 2012). Much indirect evidence for an association between working memory capacity and the level of interference produced by irrelevant distractors has come from studies on cognitive ageing, which tend to show that elderly participants are disproportionally impaired compared to younger participants at tasks that require active rejection of distracting information (Baddeley, 1996; De Fockert, 2005; De Fockert et al., 2009). Such evidence for a link between working memory capacity and selective attention is mostly indirect, as a reduction in working memory capacity in the older (vs. younger) groups is often assumed (e.g., Welford, 1958) rather than measured in these studies.

A number of studies have investigated the link between working memory capacity and distractor processing in selective attention more directly, by taking measures of working memory span in young participants, and comparing selective attention performance between groups of low and high span. A measure of a person's working memory capacity is typically obtained with a standard span task such as the Operation Span (Ospan) task (Unsworth et al., 2005). In the Ospan, participants perform number calculations while adding to a list of words they keep in memory, and working memory span is the sum of all correctly recalled word lists. In a standard Stroop task requiring naming of the ink color of printed letter strings (Stroop, 1935), interference effects produced when the letter string reads another color name are consistently greater in individuals with low, compared to those with high working memory span (Kane and Engle, 2003). Greater interference effects also occur in Eriksen-type flanker tasks in low (vs. high) span individuals (Ahmed and De Fockert, 2012b; Shipstead et al., 2012). Together, these findings suggest that having low working memory capacity has the same effect on distractibility as having a high load on working memory.

A few studies have failed to find clear evidence that low working memory span is always associated with reduced attentional selectivity. In a recent study, only one third of self-reported everyday failures of attention showed a significant correlation with working memory span (Unsworth et al., 2012), although the reported attention failures mostly involved absent-mindedness and mind wandering, rather than measures of selective attention. Another recent study found that the higher distractibility in low (vs. high) span individuals can be reversed when working memory load is manipulated at the same time (Ahmed and De Fockert, 2012b). Whereas flanker interference effects were greater in low (vs. high) span individuals when load on a concurrent working memory task was low, interference effects showed the opposite pattern under high working memory load, so that low span individuals became less distracted than those with high span. We return to this finding in the next section when we discuss possible mechanisms by which working memory may affect selective attention.

In sum, the notion that working memory plays a role in selective attention is well-supported by studies on individual differences in working memory. Perhaps more so than within-participant manipulations of working memory availability, which have produced some conflicting results, individual differences in working memory capacity are fairly consistently found to be associated with differences in selective attention, such that low working memory span is associated with reduced performance on selective attention tasks, including tasks involving ignoring potentially distracting information. A meta-analysis on the effect sizes reported in studies manipulating measuring selective attention as a function of working memory capacity shows that high working memory capacity is associated with reduced distractor interference [mean $r = 0.286$, $t_{(11)} = 7.92$, SEM $= 0.0361$, $p < 0.001$; see **Table 2**]. This finding is in line with load theory of selective attention (Lavie et al., 2004), which predicts that any reduction in the availability of working memory, be it because of high concurrent load on working memory, as discussed in the previous section, or low working memory capacity, as outlined in the current section, will compromise the ability to effectively control against processing of perceived distractors.

POSSIBLE MECHANISMS UNDERLYING THE LINK BETWEEN WORKING MEMORY AND SELECTIVE ATTENTION

Although the extant evidence clearly suggests a degree of functional overlap between working memory and selective attention, until recently the exact nature of the interaction between working memory and selective attention remained relatively underspecified. The relationship between working memory and selective attention may simply involve relying on the same limited resource pool needed both for active information maintenance in working memory and for active distractor suppression in selective attention. Alternatively, working memory may play a more specific role in selective attention, for example by maintaining clear priorities for target-related processing in selective attention (Lavie et al., 2004). Two issues will be discussed in this section. Working memory is a multi-component system, and the first question concerns whether any specific working memory component(s) are involved in selective attention, and if so, what these components might be. Second, whereas the effect of working memory on selective attention is well-documented in terms of the mere extent to which distracting information is processed, it remains unclear which functional mechanism in selective attention underlies the effect.

Which working memory component(s) may be involved in selective attention? Many studies on the role of working memory in selective attention have used verbal working memory tasks to manipulate load (e.g., Lavie et al., 2004). The finding that verbal working memory load leads to an increase in distractor processing in selective attention may point at the phonological loop of the working memory system as the key subsystem, especially since a non-verbal working memory task such as working memory for spatial locations does not always have the same effect of increasing distractibility in selective attention (Kim et al., 2005; but see Stins

Table 2 | Effect sizes (*r*) for the effect of working memory capacity on distractor processing (reaction time effects, unless stated otherwise; high vs. low score on working memory span measure, unless stated otherwise).

Source	Experiment	Effect size (*r*)	Effect of working memory capacity on
Conway et al. (2001)		**0.416**	Shadowing cost during presentation of irrelevant own name
Kane and Engle (2003)	1	**0.289**	Stroop interference (error rate)
Kane and Engle (2003)	2	**0.232**	Stroop interference with feedback (error rate)
Kane and Engle (2003)	3	**0.295**	Stroop interference
Kane and Engle (2003)	4	**0.218**	Stroop interference
De Fockert et al. (2009)		**0.535**	Interference from irrelevant faces (young vs. old participants)
Poole and Kane (2009)	1	**0.217**	Visual search in the presence of distractors
Poole and Kane (2009)	2	**0.323**	Visual search in the presence of distractors
Poole and Kane (2009)	3	**0.246**	Visual search in the presence of distractors
Shipstead et al. (2012)		**0.367**	Flanker interference in displays without placeholders
Shipstead et al. (2012)		0.020	Flanker interference in displays with placeholders
Sörqvist et al. (2012)		**0.271**	Effect of auditory deviant on target processing

In all cases, distractor processing was greater in participants with low (vs. high) working memory capacity. Effect sizes in bold are statistically significant effects at $p < 0.05$. Papers included in the meta-analysis were first identified via PubMed (search terms "working memory selective attention"). The search returned 750 articles, from which relevant papers were selected, i.e., when they measured distractor processing in selective attention as a function of working memory capacity. In addition, any relevant work was included that was cited in the selected papers, but had not been identified in the PubMed search.

et al., 2004, for evidence that high load on spatial working memory leads to more Stroop interference). Two findings, however, argue against this conclusion. First, the effect of working memory load on distractibility persists even when the phonological loop is loaded by overt rehearsal in both high and low load (Lavie et al., 2004, Experiment 2). Second, manipulations of cognitive control load other than verbal working memory also lead to increased distractibility (Lavie et al., 2004; De Fockert et al., 2010). Distractor effects are greater when there is a cost of concurrence (Navon and Gopher, 1979), such as when the task involves switching between a working memory and a selective attention task, compared to when the selective attention task is performed on its own (Lavie et al., 2004, Experiments 4 and 5). Similarly, occasionally having to make a spatially incongruent response, whilst withholding the spatially prepotent congruent response that is required on a majority of trials (a manipulation that does not load working memory), also leads to increased distractibility on a subsequent flanker task (De Fockert et al., 2010).

The findings that manipulations that involve cognitive control functions other than working memory, such as dual task performance and response inhibition, are also associated with an increase in distractor processing in selective attention, suggest that the effect of working memory in selective attention is more likely to be domain-general than domain-specific (De Fockert and Bremner, 2011). The domain-general nature of the role of working memory in selective attention is further demonstrated by the finding that verbal working memory load affects the processing of irrelevant information in tasks that are unlikely to rely on activation of verbal codes, such as visual search in the attentional capture studies (Lavie and De Fockert, 2005), and size judgments in the Ebbinghaus illusion (De Fockert and Wu, 2009) and inattentional blindness (De Fockert and Bremner, 2011). An obvious candidate for a domain-general component of working memory that is involved in selective attention is the central executive. Indeed, one of the original functions of the central executive was proposed to be selective attention to task-relevant information in the face of potential distraction by other sources (Baddeley, 1996). The central executive, however, has no direct storage role, and storage is often what is manipulated to increase load on working memory. Together with the finding that manipulations loading cognitive control functions other than working memory, including dual task performance and suppression of prepotent responses, have also been shown to increase distractor processing in selective attention, this leaves open the possibility that working memory has an indirect effect on selective attention, perhaps because it shares limited resources with cognitive control mechanisms involved in active distractor rejection. More work is needed to further explore this possibility.

Which functional mechanisms in selective attention may explain the observed variations in distractibility as a function of the availability of working memory? At least two possibilities have been suggested, based on either temporal or spatial aspects of selective attention. High load on working memory leads to a delay in the allocation of attention to target representations in visual processing (Scalf et al., 2011): the neural response in occipital cortex associated with a visual target peaked later when load on a concurrent working memory task was high (vs. low), suggesting that visual attention is deployed more slowly to the relevant target representation when working memory is otherwise engaged. Other findings support the notion that working memory availability affects the timing of attentional processes (e.g., Heitz and Engle, 2007; Poole and Kane, 2009). During the processing of flanker trials, individuals with low and high working memory capacity are initially equally distractible by irrelevant information, as they show similar accuracy for responses faster than ∼400 ms. Performance improves more rapidly however in high (vs. low) span individuals as responses get slower, which could suggest that the high span individuals are quicker to constrain attention to the relevant information (Heitz and Engle, 2007).

Working memory may also affect the way in which selective attention operates in the spatial domain. The evidence that high individuals are faster than those with a low working memory span to constrain spatial attention to task-relevant locations, thereby excluding distractors locations from processing (Heitz and Engle, 2007; Poole and Kane, 2009), suggests that both temporal and spatial aspects of selective attention are affected by working memory. High working memory capacity has also shown to allow better constraining of spatial attention over a prolonged time period (Poole and Kane, 2009). Further evidence for the notion that working memory load affects the distribution of spatial attention comes from a study using a flanker task in which distractor interference was measured at varying spatial separations between the target and the distractor under low or high working memory loads (Caparos and Linnell, 2010). High load had the effect of dispersing the characteristic spatial profile of attention in terms of facilitation and suppression zones (Müller et al., 2005). Similar findings have been reported in a flanker task while manipulating the factors of working memory load and working memory capacity simultaneously (Ahmed and De Fockert, 2012b). The spatial profile of attention was most constrained in high working memory span individuals while load on the working memory task was low. Similar, and more dispersed profiles than in the high span group under low load were observed under high load in the high span group, and under low load in the low span group. When working memory was high in the low span group, spatial attention became even less constrained. These findings all suggest that working memory is necessary to maintain a task-appropriate narrow attentional focus, and that the unavailability of working memory leads to a widening of the attentional focus. Indeed, effects of working memory load on distractibility are absent when attentional focus is experimentally manipulated to remain either narrow or wide (Chen and Chan, 2007).

The combined effect of working memory load and capacity on the spatial profile of attention can explain the seemingly contradictory findings that working memory load can have opposite effects depending on a person's working memory capacity, increasing distractibility in individuals with high working memory span, but reducing distractibility in low span individuals (Ahmed and De Fockert, 2012b). The spatial profile of attention consists of alternating facilitation and suppression zones (Müller et al., 2005), and the pattern of distractor effects as a function of both working memory load and capacity is accurately explained in terms of the region of the attentional profile (facilitation, suppression) that the distractor coincides with, giving the presumed changes in the spatial dispersion of the attentional profile as a function of working memory load and capacity. Similar changes in the spatial profile of attention may also explain the finding that interference effects from the global level of a Navon figure are increased, but interference effects from the local level are reduced by high working memory load (Ahmed and De Fockert, 2012a). A more dispersed attentional profile under high load will increase the likelihood that the global level of the Navon figure is attended, leading to greater interference when attention has to be directed toward the local level, but less interference when it has to be directed toward the global level.

In summary, the effect of working memory on selective attention is largely domain-general, and working memory and selective attention interact even when the tasks show little overlap in terms of stimulus content (but see Kim et al., 2005; Park et al., 2007, for findings suggesting domain-specific effects of working memory on selection). Moreover, there are at least two possible ways in which selective attention can be influenced by working memory. First, the temporal dynamics of attentional selection may change when working memory is unavailable for selection. Under high working memory load, activation of the representation of a visual target is delayed, leaving more opportunity for distractors to influence behavior. Similarly, low working memory capacity is associated with slower constraining of attention to task-relevant inputs, again leaving a longer time window in which distractors may be processed. Second, the spatial distribution of attention varies as a function of the availability of working memory. Spatial attention has a more constrained focus when working memory is available for attention (under low working memory load, or in individuals with high working memory span), compared to when working memory is less available (under high working memory load, or in individuals with low working memory span).

DISCUSSION

The idea that working memory and selective attention are closely related systems has become mainstream during the past decade, to the extent that they are sometimes seen as two manifestations of the same underlying system (Awh and Jonides, 2001; Awh et al., 2006; Chun, 2011). Both working memory and selective attention involve prioritization of certain information in the presence of competing inputs, and involve maintaining information across time (working memory) and space (selective attention). Furthermore, working memory and selective attention share neural systems (e.g., Gazzaley et al., 2007; Mayer et al., 2007; Gazzaley and Nobre, 2012), and people's performance on working memory and selective attention tasks shows a consistent positive correlation (e.g., Kane and Engle, 2003). The work reviewed here has found with reasonable consistency that the unavailability of working memory for selective attention, either because working memory is engaged in an additional task of high load or because there is low working memory capacity, is associated with greater distractibility in a range of selective attention tasks. This conclusion is supported by a meta-analysis of the effect sizes in studies manipulating working memory load during selective attention, which found that high working memory load tends to lead to an increase in distractor processing.

An alternative account for the observed effects of working memory on selective attention is that the increase in distractibility under high working memory load is merely due to the increase in overall task difficulty when working memory load is high. Two lines of evidence argue against this argument. First, when there is an increase in overall response latency and/or error rate under high working memory load, suggesting a general increase in task difficulty, the increase in the distractor interference effect tends to be disproportionate to the increase in the overall performance cost (e.g., Lavie et al., 2004). Second, performance that benefits from greater distractor processing should be better under high working memory load. There are a few examples that this is indeed the case. Negative priming refers to the finding that processing is impaired for recently ignored information (Tipper, 1985). Therefore, if distractors cannot be efficiently ignored under high working memory load, then negative priming effects should be reduced by high load. This is indeed the case, and the performance impairment normally observed when a previously ignored distractor is repeated as a target is eliminated by high working memory load (De Fockert et al., 2010). Another example in which performance was improved by high load on working memory is the release from inattentional blindness found when detection and identification rates for an unexpected task-irrelevant visual stimulus were measured under varying levels of working memory load (De Fockert and Bremner, 2011).

Load theory predicts opposite effects on distractibility as a function of increases in perceptual load and working memory load (Lavie et al., 2004). However, whether the constructs of perceptual load and working memory load can be clearly distinguished has been questioned, and it has been suggested that the prediction of increased distractibility under high working memory load only holds if perceptual and working memory load are independent and rely on separate resources (Tsal and Benoni, 2010). If they do not, then any additional increase in the load on attentional resources (either perceptual or cognitive) should be associated with reduced distractor processing. The evidence from studies on working memory load and working memory capacity clearly does not support this interpretation of load theory, suggesting that cognitive and perceptual load have to be regarded as separate constructs. Indeed, whereas spatial working memory and spatial selective attention may share certain resources (Awh and Jonides, 2001), there is less evidence for any direct resource competition between the types of working memory discussed here (e.g., working memory for digits) and visual selection. For example, non-overlapping cortical regions are involved in tasks of working memory for digit order and visual selection (e.g., De Fockert et al., 2001). In addition, perceptual load and working memory load are repeatedly shown to have opposite effects on selection in studies on either perceptual or working memory load, and also when both types of load are manipulated within the same experiment, distractor processing is reduced when perceptual load is high, but increased when working memory load is high (Lavie et al., 2004, Experiment 3). Other work has found a similar dissociation between the effects of the two types of load on distractor processing (Yi et al., 2004).

A number of key questions about the role of working memory in selective attention are now beginning to be addressed. First, it seems that working memory influences selection at an early stage of processing, often affecting the perception of distracting information (e.g., De Fockert and Bremner, 2011). Second, the effect of working memory on selective attention is domain-general, as loading working memory in one domain (e.g., maintaining visually presented digits) can lead to an increase in distractor processing in a different domain (e.g., processing of a color singleton or distracting circle; e.g., Lavie and De Fockert, 2005; De Fockert and Wu, 2009) or even in a different modality (e.g., audition or touch; Dalton et al., 2009a,b). Moreover, other manipulations of cognitive control (e.g., dual task performance and response suppression) affect distractor processing in a similar way to loading working memory. Third, loading working memory can affect both the temporal and the spatial deployment of attention (Caparos and Linnell, 2010; Scalf et al., 2011; Ahmed and De Fockert, 2012b).

To conclude, this paper has provided a review of the evidence for a form of attentional selection that is different from the type of selective processing, based on perceptual aspects of the input, proposed by the perceptual load and dilution models. Whereas selection can often occur passively because of the characteristics of the input (i.e., under conditions of high perceptual load or high dilution), distracting information often receives some processing and needs to be actively selected against, for example when distractors are sufficiently salient, or unexpected. In such cases of potential distraction, working memory plays a role in minimizing the interference produced by the distractors. This is but one of the ways in which working memory and selective attention are likely to interact, and other links include the role of selective attention in determining which information is encoded in working memory (e.g., Oberauer, 2003), and the finding that the contents of working memory can bias what is selected in visual processing (Soto et al., 2008). These multiple interactions emphasize the close relationship between working memory and selective attention.

REFERENCES

Ahmed, L., and De Fockert, J. W. (2012a). Working memory load can both improve and impair selective attention: evidence from the Navon paradigm. *Atten. Percept. Psychophys.* 74, 1397–1405.

Ahmed, L., and De Fockert, J. W. (2012b). Focusing on attention: the effects of working memory capacity and load on selective attention. *PLoS ONE* 7:e43101. doi: 10.1371/journal.pone.0043101

Awh, E., and Jonides, J. (2001). Overlapping mechanisms of attention and spatial working memory. *Trends Cogn. Sci.* 5, 119–126.

Awh, E., Vogel, E. K., and Oh, S.-H. (2006). Interactions between attention and working memory. *Neuroscience* 139, 201–208.

Baddeley, A. (1996). Exploring the central executive. *Q. J. Exp. Psychol.* 49A, 5–28.

Benoni, H., and Tsal, Y. (2010). Where have we gone wrong? Perceptual load does not affect selective attention. *Vision Res.* 50, 1292–1298.

Benoni, H., and Tsal, Y. (2012). Controlling for dilution while manipulating load: perceptual and sensory limitations are just two aspects of task difficulty. *Psychon. Bull. Rev.* 19, 631–638.

Berti, S., and Schröger, E. (2003). Working memory controls involuntary attention switching: evidence from an auditory distraction paradigm. *Eur. J. Neurosci.* 17, 1119–1122.

Boot, W. R., Brockmole, J. R., and Simons, D. J. (2005). Attention capture is modulated in dual-task situations. *Psychon. Bull. Rev.* 12, 662–668.

Caparos, S., Ahmed, L., Bremner, A. J., De Fockert, J. W., Linnell, K. J., and Davidoff, J. (2012). Exposure to an urban environment alters the local bias of a remote culture. *Cognition* 122, 80–85.

Caparos, S., and Linnell, K. J. (2010). The spatial focus of attention is controlled at perceptual and cognitive levels. *J. Exp. Psychol. Hum. Percept. Perform.* 36, 1080–1107.

Caparos, S., Linnell, K. J., Bremner, A. J., De Fockert, J. W., and Davidoff, J. (2013). Do local and global perceptual biases tell us anything about local and global selective attention? *Psychol. Sci.* 24, 206–212.

Carmel, D., Fairnie, J., and Lavie, N. (2012). Weight and see: loading working memory improves incidental identification of irrelevant faces. *Front. Psychology* 3:286. doi: 10.3389/fpsyg.2012.00286

Chen, Z., and Chan, C. C. (2007). Distractor interference stays constant despite variation in working memory load. *Psychon. Bull. Rev.* 14, 306–312.

Chun, M. M. (2011). Visual working memory as visual attention sustained over time. *Neuropsychologia* 49, 1407–1409.

Conway, A. R. A., Cowan, N., and Bunting, M. F. (2001). The cocktail party phenomenon revisited: the importance of working memory capacity. *Psychon. Bull. Rev.* 8, 331–335.

Dalton, P., Santangelo, V., and Spence, C. (2009a). The role of working memory in auditory selective attention. *Q. J. Exp. Psychol.* 62, 2126–2132.

Dalton, P., Lavie, N., and Spence, C. (2009b). The role of working memory in tactile selective attention. *Q. J. Exp. Psychol.* 62, 635–644.

De Fockert, J., Ramchurn, A., Van Velzen, J., Bergström, Z., and Bunce, D. (2009). Behavioural and ERP evidence of increased interference in old age. *Brain Res.* 1282, 67–73.

De Fockert, J. W. (2005). Keeping priorities: the role of working memory and selective attention in cognitive aging. *Sci. Aging Knowledge Environ.* 44, pe34.

De Fockert, J. W., and Bremner, A. J. (2011). Release of inattentional blindness by high working memory load: elucidating the relationship between working memory and selective attention. *Cognition* 121, 400–408.

De Fockert, J. W., Caparos, S., Linnell, K. J., and Davidoff, J. (2011). Reduced distractibility in a remote culture. *PLoS ONE* 6:e26337. doi: 10.1371/journal.pone.0026337

De Fockert, J. W., Mizon, G. A., and D'Ubaldo, M. A. (2010). No negative priming without cognitive control. *J. Exp. Psychol. Hum. Percept. Perform.* 36, 1333–1341.

De Fockert, J. W., Rees, G., Frith, C., and Lavie, N. (2004). Neural correlates of attentional capture in visual search. *J. Cogn. Neurosci.* 16, 751–759.

De Fockert, J. W., Rees, G., Frith, C. D., and Lavie, N. (2001). The role of working memory in visual selective attention. *Science* 291, 1803–1806.

De Fockert, J. W., and Theeuwes, J. (2012). Role of frontal cortex in attentional capture by singleton distractors. *Brain Cogn.* 80, 367–373.

De Fockert, J. W., and Wu, S. (2009). High working memory load leads to more Ebbinghaus illusion. *Eur. J. Cogn. Psychol.* 21, 961–970.

de Liaño, B., Umiltà, C., Stablum, F., Tebaldi, F., and Cantagallo, A. (2010). Attentional distractor interference may be diminished by concurrent working memory load in normal participants and traumatic brain injury patients. *Brain Cogn.* 74, 298–305.

Desimone, R., and Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annu. Rev. Neurosci.* 18, 193–222.

Engle, R. W., and Kane, M. J. (2004). "Executive attention, working memory capacity, and a two-factor theory of cognitive control," in *The Psychology of Learning and Motivation,* Vol. 44, ed B. Ross (New York, NY: Acodemic Press), 145–199.

Engle, R. W., Kane, M. J., and Tuholski, S. W. (1999). "Individual differences in working memory capacity and what they tell us about controlled attention, general fluid intelligence and functions of the prefrontal cortex," in *Models of Working Memory: Mechanisms of Active Maintenance and Executive Control,* eds A. Miyake and P. Shah (London: Cambridge Press), 102–134.

Eriksen, B. A., and Eriksen, C. W. (1974). Effects of noise letters upon identification of a target letter in a non- search task. *Percept. Psychophys.* 16, 143–149.

Gazzaley, A., and Nobre, A. C. (2012). Top-down modulation: bridging selective attention and working memory. *Trends Cogn. Sci.*16, 129–135.

Gazzaley, A., Rissman, J., Cooney, J., Rutman, A., Seibert, T., Clapp, W., et al. (2007). Functional interactions between prefrontal and visual association cortex contribute to top-down modulation of visual processing. *Cereb. Cortex* 17, 125–135.

Hasher, L., and Zacks, R. T. (1988). Working memory, comprehension, and aging: a review and a new view. *Psychol. Learn. Motiv.* 22, 122–149.

Heitz, R. P., and Engle, R. W. (2007). Focusing the spotlight: individual differences in visual attention control. *J. Exp. Psychol. Gen.* 136, 217–240.

Jongen, E. M. M., and Jonkman, L. M. (2011). Effects of concurrent working memory load on distractor processing and interference control in a name-face Stroop task. *Psychophysiology* 48, 31–43.

Kane, M. J., Bleckley, M. K., Conway, A. R., and Engle, R. W. (2001). A controlled-attention view of working-memory capacity. *J. Exp. Psychol. Gen.* 130, 169–183.

Kane, M. J., and Engle, R. W. (2003). Working-memory capacity and the control of attention: the contributions of goal neglect, response competition, and task set to Stroop interference. *J. Exp. Psychol. Gen.* 132, 47–70.

Kelley, T. A., and Lavie, N. (2011). Working memory load modulates distractor competition in primary visual cortex. *Cereb. Cortex* 21, 659–665.

Kim, S.-Y., Kim, M.-S., and Chun, M. M. (2005). Concurrent working memory load can reduce distraction. *Proc. Natl. Acad. Sci. U.S.A.* 102, 16524–16529.

Lachter, J., Forster, K. I., and Ruthruff, E. (2004). Forty-five years after Broadbent (1958): still no identification without attention. *Psychol. Rev.* 111, 880–913.

Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. *J. Exp. Psychol. Hum. Percept. Perform.* 21, 451–468.

Lavie, N. (2010). Attention, distraction and cognitive control under load. *Curr. Dir. Psychol. Sci.* 19, 143–148.

Lavie, N., and Cox, S. (1997). On the efficiency of attentional selection: efficient visual search results in inefficient rejection of distraction. *Psychol. Sci.* 8, 395–398.

Lavie, N., and De Fockert, J. W. (2005). The role of working memory in attentional capture. *Psychon. Bull. Rev.* 12, 669–674.

Lavie, N., and De Fockert, J. W. (2006). Frontal control of attentional Capture in visual search. *Vis. Cogn.* 14, 863–876.

Lavie, N., Hirst, A., De Fockert, J. W., and Viding, E. (2004). Load theory of selective attention and cognitive control. *J. Exp. Psychol. Gen.* 133, 339–354.

Lavie, N., and Tsal, Y. (1994). Perceptual load as a major determinant of the locus of selection in visual attention. *Percept. Psychophys.* 56, 183–197.

Legrain, V., Crombez, G., Verhoeven, K., and Mouraux, A. (2011). The role of working memory in the attentional control of pain. *Pain* 152, 453–459.

Macdonald, J. S. P., and Lavie, N. (2008). Load induced blindness. *J. Exp. Psychol. Hum. Percept. Perform.* 34, 1078–1091.

Mack, A., and Rock, I. (1998). *Inattentional Blindness.* London: MIT Press.

Mayer, J. S., Bittner, R. A., Nikolić, D., Bledowski, C., Goebel, R., and Linden, D. E. (2007). Common neural substrates for visual working memory and attention. *Neuroimage* 36, 441–453.

Morris, R. G., Gick, M. L., and Craik, F. I. M. (1988). Processing resources and age differences in working memory. *Mem. Cogn. 16*, 362–366.

Müller, N. G., Mollenhauer, M., Rösler, A., and Kleinschmidt, A. (2005). The attentional field has a Mexican hat distribution. *Vis. Res.* 45, 1129–1137.

Navon, D. (1977). Forest before trees: the precedence of global features in visual perception. *Cogn. Psychol.* 9, 353–383.

Navon, D., and Gopher, D. (1979). On the economy of the human processing system. *Psychol. Rev.* 86, 214–253.

Oberauer, K. (2003). Selective attention to elements in working memory. *Exp. Psychol.* 50, 257–269.

Olivers, C. N., Peters, J., Houtkamp, R., and Roelfsema, P. R. (2011). Different states in visual working memory: when it guides attention and when it does not. *Trends Cogn. Sci.* 15, 327–334.

Park, S., Kim, M. S., and Chun, M. M. (2007). Concurrent working memory load can facilitate selective attention: evidence for specialized load. *J. Exp. Psychol. Hum. Percept. Perform.* 33, 1062–1075.

Pecchinenda, A., and Heil, M. (2007). Role of working memory load on selective attention to affectively valent information. *Eur. J. Cogn. Psychol.* 19, 898–909.

Poole, B. J., and Kane, M. J. (2009). Working-memory capacity predicts the executive control of visual search among distractors: the influences of sustained and selective attention. *Q. J. Exp. Psychol.* 62, 1430–1454.

Pratt, N., Willoughby, A., and Swick, D. (2011). Effects of working memory load on visual selective attention: behavioral and electrophysiological evidence. *Front. Hum. Neurosci.* 5:57. doi: 10.3389/fnhum.2011.00057

Rabbitt, P. (1965). An age-decrement in the ability to ignore irrelevant information. *J. Gerontol.* 20, 233–238.

Roberts, B., Harris, M. G., and Yates, T. A. (2005). The roles of inducer size and distance in the Ebbinghaus illusion (Titchener circles). *Perception* 34, 847–856.

Rock, I., Linnett, C. M., Grant, P., and Mack, A. (1992). Perception without attention: results of a new method. *Cogn. Psychol.* 24, 502–534.

SanMiguel, I., Corral, M. J., and Escera, C. (2008). When loading working memory reduces distraction: behavioral and electrophysiological evidence from an auditory-visual distraction paradigm. *J. Cogn. Neurosci.* 20, 1131–1145.

Scalf, P. E., Dux, P. E., and Marois, R. (2011). Working memory encoding delays top-down attention to visual cortex. *J. Cogn. Neurosci.* 23, 2593–2604.

Shipstead, Z., Harrison, T. L., and Engle, R. W. (2012). Working memory capacity and visual attention: top-down and bottom-up guidance. *Q. J. Exp. Psychol.* 65, 401–407.

Sörqvist, P., Nöstl, A., and Halin, N. (2012). Working memory capacity modulates habituation rate: evidence from a cross-modal auditory distraction paradigm. *Psychon. Bull. Rev.* 19, 245–250.

Soto, D., Hodsoll, J., Rotshtein, P., and Humphreys, G. W. (2008). Automatic guidance of attention from working memory. *Trends Cogn. Sci.* 12, 342–348.

Stins, J. F., Vosse, S., Boomsma, D. I., and de Geus, E. J. (2004). On the role of working memory in response interference. *Percept. Mot. Skills* 99, 947–958.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *J. Exp. Psychol.* 18, 643–662.

Theeuwes, J. (1992). Perceptual selectivity for color and form. *Percept. Psychophys.* 51, 599–606.

Theeuwes, J. (2010). Top-down and bottom-up control of visual selection. *Acta Psychol.* 123, 77–99.

Tipper, S. (1985). The negative priming effect: Inhibitory priming by ignored objects. *Q. J. Exp. Psychol. A* 37, 571–590.

Tsal, Y., and Benoni, H. (2010). Diluting the burden of load: perceptual load effects are simply dilution effects. *J. Exp. Psychol. Hum. Percept. Perform.* 36, 1645–1656.

Tsuchida, Y., Katayama, J., and Murohashi, H. (2012). Working memory capacity affects the interference control of distractors at auditory gating. *Neurosci. Lett.* 516, 62–66.

Unsworth, N., Heitz, R. P., Schrock, J. C., and Engle, R. W. (2005). An automated version of the operation span task. *Behav. Res. Methods* 37, 498–505.

Unsworth, N., McMillan, B. D., Brewer, G. A., and Spillers, G. J. (2012). Everyday attention failures: an individual differences investigation. *J. Exp. Psychol. Learn. Mem. Cogn.* 38, 1765–1772.

Welford, A. T. (1958). *Ageing and Human Skill*. London: Oxford University Press.

Wilson, D. E., Muroi, M., and MacLeod, C. M. (2011). Dilution, not load, affects distractor processing. *J. Exp. Psychol. Hum. Percept. Perform.* 37, 319–335.

Yi, D. J., Woodman, G. F., Widders, D., Marois, R., and Chun, M. M. (2004). The neural fate of ignored stimuli: dissociable effects of perceptual and working memory load. *Nat. Neurosci.* 7, 992–996.

Young, A. W., Ellis, A. W., Flude, B. M., McWeeny, K. H., and Hay, D. C. (1986). Face–name interference. *J. Exp. Psychol. Hum. Percept. Perform.* 12, 466–475.

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Distraction and mind-wandering under load

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Attention research over the last several decades has provided rich insights into the determinants of distraction, including distractor characteristics, task features, and individual differences. Load Theory represented a particularly important breakthrough, highlighting the critical role of the level and nature of task-load in determining both the efficiency of distractor rejection and the stage of processing at which this occurs. However, until recently studies of distraction were restricted to those measuring rather specific forms of distraction by external stimuli which I argue that, although intended to be irrelevant, were in fact task-relevant. In daily life, attention may be distracted by a wide range of stimuli, which may often be entirely unrelated to any task being performed, and may include not only external stimuli but also internally generated stimuli such as task-unrelated thoughts. This review outlines recent research examining these more general, entirely task-irrelevant, forms of distraction within the framework of Load Theory. I discuss the relation between different forms of distraction, and the universality of load effects across different distractor types and individuals.

Keywords: attention, distractor interference, irrelevant distraction, mind-wandering, perceptual load, task-unrelated thought

The experience of being unintentionally distracted from an intended focus is likely to be frustratingly familiar to most people, and such distraction can prove highly disruptive in a variety of daily life contexts (e.g., education, Rabiner et al., 2004; in the workplace, Wallace and Vodanovich, 2003; or while driving, Arthur and Doverspike, 1992). Over the past decades a large body of research has investigated the determinants of the ability to focus attention on relevant stimuli, while avoiding distraction from irrelevant stimuli, highlighting a number of important factors. These include features of the distractor such as visual salience or abrupt onset in the display (e.g., Theeuwes, 1992; Yantis, 2000) and individual differences (e.g., in working memory capacity (WMC); Kane and Engle, 2003). The level of perceptual load in a task has been identified as a particularly powerful determinant of distraction: according to the Load Theory (e.g., Lavie, 1995, 2005, 2010), irrelevant (and potentially distracting) stimuli can only be perceived if there is sufficient spare perceptual capacity left over from task processing. Distraction can therefore be reduced or altogether avoided during more perceptually demanding tasks, which fully exhaust perceptual capacity and so reduce or prevent distractor processing. In contrast, tasks which impose only a low level of perceptual load leave spare capacity, which allows processing of potentially distracting non-task stimuli.

In support of Load Theory, increased perceptual load (in terms of a greater number of task stimuli requiring processing, or more complex perceptual task demands) has been found to reduce both the visual-cortical response to irrelevant stimuli (e.g., Yi et al., 2004; Schwartz et al., 2005), and a range of behavioral indices of distractor processing including response-competition (e.g., Lavie, 1995; Lavie and Cox, 1997), negative priming (Lavie and Fox, 2000), and inattentional blindness (Cartwright-Finch and Lavie, 2007). However, as I shall discuss, until recently empirical studies of perceptual load effects, and of distraction in general, were limited to those using external distractor stimuli that were in some way relevant to the task being performed. Load Theory implies that under low load even entirely task-irrelevant stimuli will be processed and could potentially (providing that they are of sufficient salience) cause distraction. Indeed, in daily life, people may often be distracted by stimuli seemingly entirely unrelated to the task that they are currently engaged in – for example a student may be distracted from studying by the sight of a friend walking by. In addition, task-irrelevant distractions may come not only from the external environment but also from internally generated stimuli associated with mind-wandering – for example, a student may be distracted from reading an assigned article by the intrusion of a thought about an unrelated issue – perhaps some salient recent event in his or her daily life. In the following sections I consider the extent to which both well established and more recent laboratory measures address the common daily life experience of entirely task-irrelevant distraction (by both internal and external stimuli), and discuss recent studies extending Load Theory to these forms of distraction.

ESTABLISHED MEASURES OF DISTRACTION

A widely used measure of distraction is the response-competition task (e.g., Eriksen and Eriksen, 1974; see **Figure 1A** for example). Within this task, participants are slowed in responding to targets in the presence of response-incompatible versus response-compatible distractors. In contrast to predecessors such as the Stroop task (Stroop, 1935), the target and distractors are presented in spatially separate locations which are known to the participant. As the target location is known, participants have no reason to search the distractor locations, making these locations entirely irrelevant.

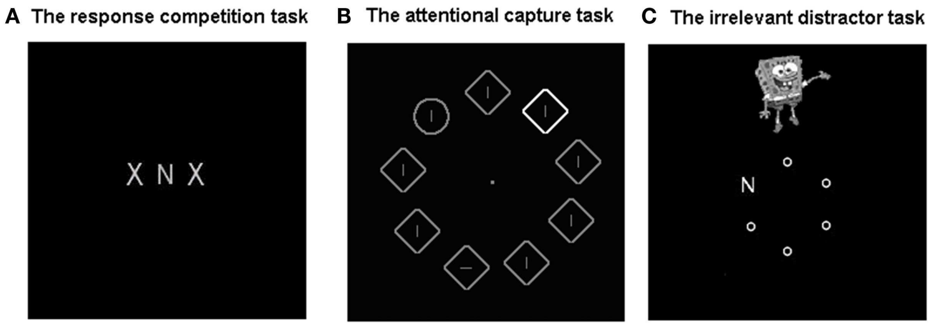

FIGURE 1 | Measures of distractor interference: example displays. **(A)** The response-competition-task. In this task participants make forced-choice responses to a target item (in this example, either X or N). Distraction is indexed by the RT increase when the target item is flanked by distractors representing the competing response (pictured) versus those representing the same response. **(B)** The attentional capture task. In the typical attentional capture task, distraction is indexed by the increase in search RTs for a target item (in this example a circle), when one of the non-target search items appears as a salient singleton in an irrelevant dimension (e.g., color), compared to a no singleton baseline. **(C)** A new measure of interference from salient yet entirely task-irrelevant distractors. Within these measures distraction is indexed by the increase in RTs associated with the peripheral presentation of a colorful distractor. This can be either an image of a well known cartoon character (selected from Superman, Spiderman, Pikachu, Spongebob Squarepants, Micky Mouse, and Donald Duck) or meaningless yet colorful shape.

In this way the response-competition task appears to reflect situations in daily life in which an individual is distracted by a stimulus appearing in an unattended location. However, although the location is irrelevant, the identity of response-competition distractors is highly relevant to the task. In the most typical versions of the task the distractor stimuli are of the same type as target (e.g., both are letters), although some versions of the task use different stimulus types (e.g., pictures versus names) as target and distractor (e.g., Young et al., 1986). Nevertheless, by the very nature of the response-competition task all variants of this task have in common a strong response-relevance born by the distractor to the target. Interestingly, it has been demonstrated that the expected locations of response-competition distractors in fact appear to receive advance attentional allocation (resulting in speeded perception of other stimuli appearing in these locations, Tsal and Makovski, 2006). In these respects, the response-competition task differs somewhat from the kind of interference often experienced in daily life, from a distractor (e.g., a friend walking past) that is entirely unrelated to the task being performed (e.g., studying).

The question as to whether any task-irrelevant stimuli can nevertheless attract and distract attention has in fact been the focus of a contentious debate for some time, triggering the development of another widely used class of distraction measure: the Attentional Capture Paradigm (see **Figure 1B** for example). Using variants of this task, reaction time (RT) interference has been demonstrated in the presence (versus absence) of certain types of distractor, such as salient feature singletons (e.g., Theeuwes, 1991a, 1992) and abrupt onsets (e.g., Remington et al., 1992), even when these are response-irrelevant and visually distinct from the target stimuli. However, proponents of "contingent capture" have challenged studies purporting to show attentional capture from irrelevant stimuli, highlighting that even apparently task-irrelevant distractors may in fact be relevant to attentional settings for the task (e.g., Folk et al., 1992, 2002), and moreover, their ability to interfere may depend on this task-relevance. For example, interference from singleton distractors may be contingent on their relevance to a "singleton detection" search strategy adopted when the search target is also a singleton (even in a different dimension – e.g., color versus form; Bacon and Egeth, 1994). Task-relevance may also be conferred by more general aspects of the stimulus display: Gibson and Kelsey (1998) have argued, for example, that any task involving an onset of the stimulus display at the start of each trial may create "display-wide" attentional settings for abrupt onset stimuli, including distractors.

In addition, studies designed to demonstrate distraction by stimuli irrelevant to any attentional settings have primarily used search tasks in which the distractors appear in task-relevant locations, in or around potential target locations. As the specific target location is typically unknown, participants would be likely to allocate their attention diffusely across the entire display, including the locations in which the distractors were to appear. In the light of previous evidence suggesting that distractor effects can be eliminated with prior knowledge of location (Yantis and Jonides, 1990; Theeuwes, 1991b), it seems likely that location-relevance contributes to the distractor interference measured by such paradigms. A smaller number of studies (Christ and Abrams, 2006; Neo and Chua, 2006) have demonstrated attentional capture by abrupt onsets within paradigms in which the target location is known. However, even in these cases the location was not in fact entirely irrelevant – distractors and other non-targets were perceptually grouped with the target around fixation, which would have made them harder to ignore (see Driver and Baylis, 1989; Kramer and Jacobson, 1991).

IRRELEVANT DISTRACTION: EXTERNAL SOURCES

The studies reviewed above highlight that in order to be considered entirely task-irrelevant, distractors must be unrelated to any task responses, presented in an irrelevant location, visually dissimilar from the search stimuli and irrelevant to any attentional settings for the current task. A recent series of studies by Forster and Lavie (2008a,b, 2011) (see **Figure 1C**) introduced a new measure designed to meet these criteria. These studies have demonstrated robust RT slowing in the presence, versus absence, of a colorful distractor image (e.g., of the cartoon character Spiderman) across two different task types: a letter search (Forster and Lavie, 2008a,b) and a sequential forced-choice response task (Forster and Lavie, 2011; **Figure 2**). Irrelevant distractor interference has been found for meaningless (a colorful shape) and frequently presented (50% trials) stimuli, but was greater for semantically meaningful (e.g., a famous cartoon character) and infrequently presented (10% trials) stimuli (Forster and Lavie, 2008b, see also Biggs et al., 2012 for further examination of effects of meaningfulness on irrelevant distraction).

Note that in these studies, the complex and colorful distractor stimuli bore no visual similarity to the task stimuli (gray letters or digits), appeared in an irrelevant peripheral location, and were unrelated in content to any aspect of the task being performed. Although the distractor was a type of singleton (being the only stimulus of its kind in the display), the interference does not appear to depend on a use of a singleton detection search strategy as it persists even when such a strategy is unavailable (using a search set size of three; Forster and Lavie, 2008a,b). In addition, the brief onset of the irrelevant distractor during a novel sequential response task (see **Figure 2**) produced RTs slowing of up to three responses following its presentation. As the display in this task remained constant over multiple (9 or 36) responses, such interference cannot be attributed to attentional settings associated with onset of, or other dynamic changes to, the task stimuli. Thus, as in daily life, the distractors in these studies appear to interfere despite being entirely task-irrelevant.

Forster and Lavie (2008a) recently clarified that although interference from these salient and meaningful abrupt onset distractors persists in the absence of any task-relevance, it can be modulated by perceptual task-load. This study employed a widely used manipulation of load with a letter search task, whereby a letter search target is presented among non-targets that are either visually dissimilar (e.g., small circles, low load, see **Figure 1C**) or similar (e.g., other angular letters, high load) to the target. I note that this manipulation of load within response-competition tasks has recently been argued to reduce interference not via load, but via low level "dilution" effects whereby feature representations of the visually similar non-targets degrade the distractor representation (e.g., Tsal and Benoni, 2010; Wilson et al., 2011). Unlike response-competition letter distractors, however, the irrelevant distractors have very minimal feature overlap with the non-target stimuli in either the high or low load conditions. It appears less plausible that the inclusion of small, monochromatic letters (versus small, monochromatic circles) in the display would substantially degrade the representation of a larger, colorful cartoon image. Thus, the finding that the robust irrelevant distractor interference seen under low load can be reduced to non-significant levels under high load provides compelling evidence in support of the perceptual load hypothesis.

IRRELEVANT DISTRACTION: INTERNAL SOURCES

In daily life sources of distraction may not only be found in the external environment, but also in the form of internally generated distractions such as task-unrelated thoughts (TUTs). Studies of mind-wandering suggest that this may be a highly disruptive form of distraction: increased reports of TUTs have been associated with impaired performance on a wide range of tasks from simple signal detection to more complex tasks such reading comprehension, listening to lectures, SAT examinations, and driving (Schooler et al.,

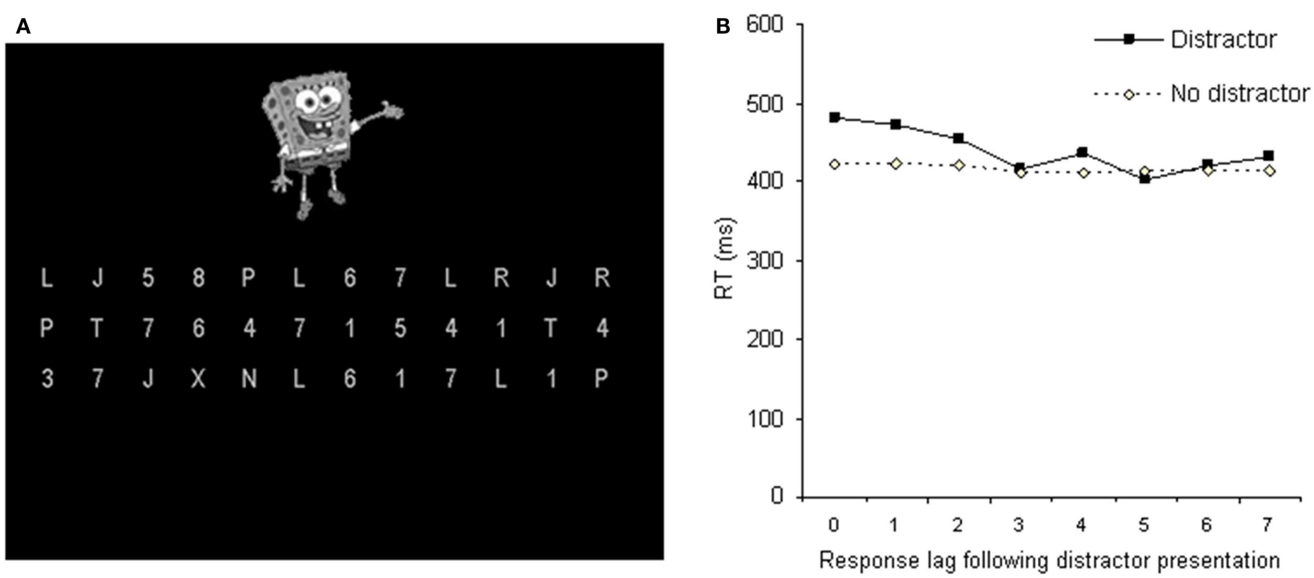

FIGURE 2 | A continuous task designed to preclude general attentional settings associated with the onset of the display. (A) Example stimulus display: participants make sequential responses, working from left to right, top to bottom, indicating whether each item in the display is a letter or a digit. The display remains onscreen throughout the response sequence. The distractor appears briefly during a minority of displays, and never co-occurs with the responses immediately following the display onset. **(B)** Despite being entirely irrelevant to the task in terms of visual appearance, meaning, location, and any attentional settings, the brief presentation of a distractor produces significant RT slowing for the response immediately following its presentation (lag 0), and for the two subsequent responses (lags 1 and 2).

2004; Smallwood et al., 2007; He et al., 2011; Risko et al., 2012; Unsworth et al., 2012).

Despite its apparent ubiquity in daily life, irrelevant distraction from task-unrelated mind-wandering has been largely neglected by studies of selective attention – perhaps due to the inherent difficulty in directly measuring such a subjective phenomenon. However, the growing literature on mind-wandering has established a number of measures, such as diary-keeping, questionnaires, or intermittent "thought-probing" during a task (see Smallwood and Schooler, 2006, for review), and recent individual differences research using these measures suggests that distraction from mind-wandering and external stimuli may be driven, at least in part, by common mechanisms. Kane and colleagues have argued that the ability to exert attentional control over mind-wandering draws on an executive control mechanism (e.g., McVay and Kane, 2010), which also supports attentional control over external stimuli (e.g., during Stroop or response-competition tasks, Kane and Engle, 2003; Levinson et al., 2012; Shipstead et al., 2012). In support of this claim, lower executive WMC has been linked to increased mind-wandering (e.g., Kane et al., 2007; McVay and Kane, 2009). Consistent with the notion of a role of WMC in avoiding distraction from mind-wandering, this relationship has been found to be strongest during tasks that participants classified as requiring concentration (Kane et al., 2007).

A more direct link between internal and external forms of distraction was made in a recent study (Forster and Lavie, 2013) examining the relation between individual differences in mind-wandering and two measures of external distraction: response-competition interference, and our recently established measure of entirely irrelevant distraction (as described above; Forster and Lavie, 2008a,b). In two experiments, individuals who reported higher levels of daily life mind-wandering also showed increased RT interference from task-irrelevant external distractors. However, this study highlighted that not all forms of distraction are alike: mind-wandering was not related to response-competition interference in either experiment. Moreover, interference from response-competition letter distractors was unrelated to our measure of task-irrelevant distractor interference. Thus, this study suggests a common trait specifically underlying the ability to ignore entirely irrelevant stimuli, regardless of whether these are internal (i.e., TUTs) or external, while also highlighting the importance of task-relevance in determining distraction.

An interesting question is whether, in addition to (in some cases) drawing on a common trait, internal, and external forms of distraction also share the common determinant of perceptual load. Recent studies (Forster and Lavie, 2009; Levinson et al., 2012) have examined this issue: during a letter search task with high and low perceptual load, participants were intermittently probed as to whether their current thought was task-related or task-unrelated. In keeping with the well established effects on external distraction, reports of TUTs were reduced with the increase in perceptual load. Moreover, one experiment incorporating both thought probes and response-competition distractors (Forster and Lavie, 2009, Experiment 4) demonstrated that the extent of load effects on these two forms of distraction was correlated between individuals. Thus, both internal and external forms of distraction appear subject to modulation by a common mechanism, depending on the level of perceptual load in the current task.

I note that the substantial qualitative differences between response-competition distractors and TUTs make it somewhat implausible that this common mechanism involves low level "dilution" of both types of distractor representation by the letter non-targets: indeed, it is difficult to conceive of a situation in which the representation of a TUT (e.g., involving salient current concern, Smallwood and Schooler, 2006) would be diluted simply by the presence of five externally presented monochromatic letters. Rather, the results of this study appear in line with the suggestion that when perceptual capacity is exhausted by task demands, vulnerability to interference from potential distractors is reduced regardless of whether these are internal or external.

HOW UNIVERSAL ARE PERCEPTUAL LOAD EFFECTS ON DISTRACTION?

Perceptual load is well established to modulate interference from response-competition distractors, whether these are presented in irrelevant peripheral locations (e.g., Lavie, 1995; Lavie and Cox, 1997), or fixation (Beck and Lavie, 2005); and whether these are simple letters as per the traditional response-competition task, or meaningful images (Lavie et al., 2003). The studies described above extend Load Theory to forms of distraction (both internal and external) which produce robust interference despite their irrelevance to the current task. The common effect of perceptual load on mind-wandering and response-competition interference is particularly striking given that these two forms of distraction do not appear to be directly correlated with each other (Forster and Lavie, 2009, 2013). This suggests that load effects may be universal across distractor types, regardless of their task-relevance or their relation to each other. Indeed, neuro-imaging findings suggest that perceptual load can also reduce processing even of potentially biologically important yet irrelevant stimuli, such as the amygdala response to threat (Bishop et al., 2007) and motion processing in V5 (Rees et al., 1997), as well as behavioral interference from moving or abrupt onset distractors (Cosman and Vecera, 2009, 2010).

Interestingly, the one potential exception to perceptual load effects appears to be distractor stimuli with which participants have a high degree of familiarity or expertise: response-competition interference from famous faces and musical instruments among musicians (but not non-musicians), as well as interference from task-irrelevant national flags or sports team logos, has been found to persist under high perceptual load (Lavie et al., 2003; Ro et al., 2009; Biggs et al., 2012). Thus, when stimuli have a high degree of personal relevance, they may be prioritized for processing regardless of perceptual load or task-relevance.

Perceptual load effects also appear to be largely universal across individuals, with one important exception: as load effects depend on capacity limits, individual differences in perceptual capacity (e.g., those associated with age, Maylor and Lavie, 1998; Huang-Pollock et al., 2002; video game expertise, Green and Bavelier, 2003; or conditions such as autism or congenital deafness, Proksch and Bavelier, 2002; Remington et al., 2009) lead to differences in the level of load required to reduce distraction. However, factors predicting vulnerability to distraction, such as self-reported daily life attentional failures, trait anxiety, and WMC, have been found to do so only during tasks with low load, and not high load (Bishop et al., 2007; Forster and Lavie, 2007; Bishop, 2009; Levinson et al., 2012).

CONCLUSIONS

The findings discussed here highlight the importance of considering the role of task-relevance in distraction. Although certain forms of distraction may be contingent on their task-relevance, studies using new measures demonstrate that task-relevance is not a necessary condition for distraction. Rather, as in daily life, sources of distraction may be entirely task-irrelevant, and may also include both external stimuli and task-unrelated mind-wandering. It is unclear to what extent these common, yet understudied, forms of distraction are directly related to other laboratory measures such as the response-competition task. However, perceptual load appears a powerful and largely universal determinant of distraction, across both existing measures and new measures of irrelevant distraction (both internal and external), as well as across individuals. Thus, Load Theory provides a useful framework for predicting when a variety of forms of daily life distraction are most likely to occur (i.e., during tasks with low perceptual complexity and demands) and even for interventions to prevent this (e.g., by increasing perceptual complexity).

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REFERENCES

Arthur, W., and Doverspike, D. (1992). Locus of control and auditory selective attention as predictors of driving accident involvement – a comparative longitudinal investigation. *J. Safety Res.* 23, 73–80.

Bacon, W. F., and Egeth, H. E. (1994). Overriding stimulus-driven attentional capture. *Percept. Psychophys.* 55, 485–496.

Biggs, A. T., Kreager, R. D., Gibson, B. S., Villano, M., and Crowell, C. R. (2012). Semantic and affective salience: the role of meaning and preference in attentional capture and disengagement. *J. Exp. Psychol. Hum. Percept. Perform.* 38, 531–541.

Bishop, S. J. (2009). Trait anxiety and impoverished prefrontal control of attention. *Nat. Neurosci.* 12, 92–98.

Bishop, S. J., Jenkins, R., and Lawrence, A. (2007). The neural processing of task-irrelevant fearful faces: effects of perceptual load and individual differences in trait and state anxiety. *Cereb. Cortex* 17, 1595–1603.

Cartwright-Finch, U., and Lavie, N. (2007). The role of perceptual load in inattentional blindness. *Cognition* 102, 321–340.

Christ, S. E., and Abrams, R. A. (2006). Abrupt onsets cannot be ignored. *Psychon. Bull. Rev.* 13, 875–880.

Cosman, J. D., and Vecera, S. P. (2009). Perceptual load modulates attentional capture by abrupt onsets. *Psychon. Bull. Rev.* 16, 404–410.

Cosman, J. D., and Vecera, S. P. (2010). Attentional capture by motion onsets is modulated by perceptual load. *Atten. Percept. Psychophys.* 72, 2096–2105.

Driver, J., and Baylis, G. C. (1989). Movement and visual-attention – the spotlight metaphor breaks down. *J. Exp. Psychol. Hum. Percept. Perform.* 15, 448–456.

Eriksen, B. A., and Eriksen, C. W. (1974). Effects of noise letters upon identification of a target letter in a nonsearch task. *Percept. Psychophys.* 16, 143–149.

Folk, C. L., Leber, A. B., and Egeth, H. E. (2002). Made you blink! Contingent attentional capture produces a spatial blink. *Percept. Psychophys.* 64, 741–753.

Folk, C. L., Remington, R. W., and Johnston, J. C. (1992). Involuntary covert orienting is contingent on attentional control settings. *J. Exp. Psychol. Hum. Percept. Perform.* 18, 1030–1044.

Forster, S., and Lavie, N. (2007). High perceptual load makes everybody equal – eliminating individual differences in distractibility with load. *Psychol. Sci.* 18, 377–381.

Forster, S., and Lavie, N. (2008a). Failures to ignore entirely irrelevant distractors: the role of load. *J. Exp. Psychol. Appl.* 14, 73–83.

Forster, S., and Lavie, N. (2008b). Attentional capture by entirely irrelevant distractors. *Vis. Cogn.* 16, 200–214.

Forster, S., and Lavie, N. (2009). Harnessing the wandering mind: the role of perceptual load. *Cognition* 111, 345–355.

Forster, S., and Lavie, N. (2011). Entirely irrelevant distractors can capture and captivate attention. *Psychon. Bull. Rev.* 18, 1064–1070.

Forster, S., and Lavie, N. (2013). Distracted by your mind? Individual differences in distractibility predict mind wandering. *J. Exp. Psychol. Learn. Mem. Cogn.*

Gibson, B. S., and Kelsey, E. M. (1998). Stimulus-driven attentional capture is contingent on attentional set for displaywide visual features. *J. Exp. Psychol. Hum. Percept. Perform.* 24, 699–706.

Green, C., and Bavelier, D. (2003). Action video game modifies visual selective attention. *Nature* 423, 534–537.

He, J., Becic, E., Lee, Y. C., and McCarley, J. S. (2011). Mind wandering behind the wheel: performance and oculomotor correlates. *Hum. Factors* 53, 13–21.

Huang-Pollock, C. L., Carr, T. H., and Nigg, J. T. (2002). Development of selective attention: perceptual load influences early versus late attentional selection in children and adults. *Dev. Psychol.* 38, 363–375.

Kane, M. J., Brown, L. H., McVay, J. C., Silvia, P. J., Myin-Germeys, I., and Kwapil, T. R. (2007). For whom the mind wanders, and when: an experience sampling study of working memory and executive control in everyday life. *Psychol. Sci.* 18, 614–621.

Kane, M. J., and Engle, R. W. (2003). Working-memory capacity and the control of attention: the contributions of goal neglect, response competition, and task set to Stroop interference. *J. Exp. Psychol. Gen.* 132, 47–70.

Kramer, A. F., and Jacobson, A. (1991). Perceptual organization and focused attention – the role of objects and proximity in visual processing. *Percept. Psychophys.* 50, 267–284.

Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. *J. Exp. Psychol. Hum. Percept. Perform.* 21, 451–468.

Lavie, N. (2005). Distracted and confused? Selective attention under load. *Trends Cogn. Sci. (Regul. Ed.)* 9, 75–82.

Lavie, N. (2010). Attention, distraction, and cognitive control under load. *Curr. Dir. Psychol. Sci.* 19, 143–148.

Lavie, N., and Cox, S. (1997). On the efficiency of visual selective attention: efficient visual search leads to inefficient distractor rejection. *Psychol. Sci.* 8, 395–398.

Lavie, N., and Fox, E. (2000). The role of perceptual load in negative priming. *J. Exp. Psychol. Hum. Percept. Perform.* 26, 1038–1052.

Lavie, N., Ro, T., and Russell, C. (2003). The role of perceptual load in processing distractor faces. *Psychol. Sci.* 14, 510–515.

Levinson, D. B., Smallwood, J., and Davidson, R. J. (2012). The persistence of thought: evidence for a role of working memory in the maintenance of task-unrelated thinking. *Psychol. Sci.* 23, 375–380.

Maylor, E. A., and Lavie, N. (1998). The influence of perceptual load on age differences in selective attention. *Psychol. Aging* 13, 563–573.

McVay, J. C., and Kane, M. J. (2009). Conducting the train of thought: working memory capacity, goal neglect, and mind wandering in an executive-control task. *J. Exp. Psychol. Learn. Mem. Cogn.* 35, 196–204.

McVay, J. C., and Kane, M. J. (2010). Does mind-wandering reflect executive function or executive failure? comment on Smallwood and Schooler (2006) and Watkins (2008). *Psychol. Bull.* 136, 188–197.

Neo, G., and Chua, F. K. (2006). Capturing focused attention. *Percept. Psychophys.* 68, 1286–1296.

Proksch, J., and Bavelier, D. (2002). Changes in the spatial distribution of visual attention after early deafness. *J. Cogn. Neurosci.* 14, 687–701.

Rabiner, D. L., Murray, D. W., Schmid, L., and Malone, P. S. (2004). An exploration of the relationship between ethnicity, attention problems, and academic achievement. *School Psychol. Rev.* 33, 498–509.

Rees, G., Frith, C. D., and Lavie, N. (1997). Modulating irrelevant motion perception by varying attentional load in an unrelated task. *Science* 278, 1616–1619.

Remington, A., Swettenham, J., Campbell, R., and Coleman, M. (2009). Selective attention and perceptual load in autism spectrum disorder. *Psychol. Sci.* 20, 1388–1393.

Remington, R. W., Johnston, J. C., and Yantis, S. (1992). Involuntary attentional capture by abrupt onsets. *Percept. Psychophys.* 51, 279–290.

Risko, E. F., Anderson, N., Sarwal, A., Engelhardt, M., and Kingstone, A. (2012). Everyday attention: variation in mind wandering and memory in a lecture. *Appl. Cogn. Psychol.* 26, 234–242.

Ro, T., Friggel, A., and Lavie, N. (2009). Musical expertise modulates the effects of visual perceptual load. *Atten. Percept. Psychophys.* 71, 671–674.

Schooler, J. W., Reichle, E. D., and Halpern, D. V. (2004). "Zoning out while reading: evidence for dissociations between experience and metaconsciousness," in *Thinking and Seeing: Visual Metacognition in Adults and Children*, ed. D. T. Levin (Cambridge, MA: MIT Press), 203–226.

Schwartz, S., Vuilleumier, P., Hutton, C., Maravita, A., Dolan, R. J., and Driver, J. (2005). Attentional load and sensory competition in human vision: modulation of fMRI responses by load at fixation during task-irrelevant stimulation in the peripheral visual field. *Cereb. Cortex* 15, 770–786.

Shipstead, Z., Harrison, T. L., and Engle, R. W. (2012). Working memory capacity and visual attention: top-down and bottom-up guidance. *Q. J. Exp. Psychol. (Hove)* 65, 401–407.

Smallwood, J., McSpadden, M., and Schooler, J. W. (2007). The lights are on but no one's home: meta-awareness and the decoupling of attention when the mind wanders. *Psychon. Bull. Rev.* 14, 527–533.

Smallwood, J., and Schooler, J. W. (2006). The restless mind. *Psychol. Bull.* 132, 946–958.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *J. Exp. Psychol.* 12, 643–662.

Theeuwes, J. (1991a). Cross-dimensional perceptual selectivity. *Percept. Psychophys.* 50, 184–193.

Theeuwes, J. (1991b). Exogenous and endogenous control of attention – the effect of visual onsets and offsets. *Percept. Psychophys.* 49, 83–90.

Theeuwes, J. (1992). Perceptual selectivity for color and form. *Percept. Psychophys.* 51, 599–606.

Tsal, Y., and Benoni, H. (2010). Diluting the burden of load: perceptual load effects are simply dilution effects. *J. Exp. Psychol. Hum. Percept. Perform.* 36, 1645–1656.

Tsal, Y., and Makovski, T. (2006). The attentional white bear phenomenon: the mandatory allocation of attention to expected distractor locations. *J. Exp. Psychol. Hum. Percept. Perform.* 32, 351–363.

Unsworth, N., Brewer, G. A., and Spillers, G. J. (2012). Variation in cognitive failures: an individual differences investigation of everyday attention and memory failures. *J. Mem. Lang.* 67, 1–16.

Wallace, J. C., and Vodanovich, S. J. (2003). Can accidents and industrial mishaps be predicted? Further investigation into the relationship between cognitive failure and reports of accidents. *J. Bus. Psychol.* 17, 503–514.

Wilson, D. E., MacLeod, C. M., and Muroi, M. (2011). Dilution, not load, affects distractor processing. *J. Exp. Psychol. Hum. Percept. Perform.* 37, 319–335.

Yantis, S. (2000). "Goal-directed and stimulus-driven determinants of attentional control," in *Attention and Performance*, Vol. 18, ed. S. Monsell (Cambridge, MA: MIT Press), 73–103.

Yantis, S., and Jonides, J. (1990). Abrupt visual onsets and selective attention – voluntary versus automatic allocation. *J. Exp. Psychol. Hum. Percept. Perform.* 16, 121–134.

Yi, D. J., Woodman, G. F., Widders, D., Marois, R. and Chun, M. M. (2004). Neural fate of ignored stimuli: dissociable effects of perceptual and working memory load. *Nat. Neurosci.* 7, 992–996.

Young, A. W., Ellis, A. W., Flude, B. M., McWeeny, K. H., and Hay, D. C. (1986). Face name interference. *J. Exp. Psychol. Hum. Percept. Perform.* 12, 466–475.

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Enhancement and suppression in the visual field under perceptual load

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The perceptual load theory of attention proposes that the degree to which visual distractors are processed is a function of the attentional demands of a task—greater demands increase filtering of irrelevant distractors. The spatial configuration of such filtering is unknown. Here, we used steady-state visual evoked potentials (SSVEPs) in conjunction with time-domain event-related potentials (ERPs) to investigate the distribution of load-induced distractor suppression and task-relevant enhancement in the visual field. Electroencephalogram (EEG) was recorded while subjects performed a foveal go/no-go task that varied in perceptual load. Load-dependent distractor suppression was assessed by presenting a contrast reversing ring at one of three eccentricities (2, 6, or 11°) during performance of the go/no-go task. Rings contrast reversed at 8.3 Hz, allowing load-dependent changes in distractor processing to be tracked in the frequency-domain. ERPs were calculated to the onset of stimuli in the load task to examine load-dependent modulation of task-relevant processing. Results showed that the amplitude of the distractor SSVEP (8.3 Hz) was attenuated under high perceptual load (relative to low load) at the most proximal (2°) eccentricity but not at more eccentric locations (6 or 11°). Task-relevant ERPs revealed a significant increase in N1 amplitude under high load. These results are consistent with a center-surround configuration of load-induced enhancement and suppression in the visual field.

Keywords: attention, perceptual load, steady-state visual evoked potential (SSVEP), N1

Under natural viewing conditions, the visual field is cluttered with a multitude of salient yet irrelevant stimuli. Only a subset of these stimuli are relevant for a given behavior or goal. As such, the visual system constantly performs the complex process of selecting behaviorally relevant stimuli whilst ignoring extraneous stimuli. This process of enhancing apposite stimuli and suppressing irrelevant stimuli is known as selective attention. Studies of selective visual attention have shown that when attention (not necessarily gaze) is directed to a peripheral spatial location, manual responses occur more rapidly (Posner, 1980; Posner et al., 1980) and attended stimuli are perceived as more vibrant (Prinzmetal et al., 1997, 1998; Carrasco et al., 2004; Liu et al., 2009), effects attributable to an enhanced neural response within extrastriate visual cortex (Kastner et al., 1998; Martinez et al., 1999; Silver et al., 2007). In addition to the enhanced visual responses at attended regions, neural representations of space adjacent to an attended location are inhibited, indicating that attention takes on a center-surround configuration, enhancing attended space and suppressing the surrounding area (Müller and Kleinschmidt, 2004; Müller et al., 2005; Hopf et al., 2006; Boehler et al., 2009).

Attentional enhancement and suppression of stimuli in the visual field does not occur invariably but is modulated by the demands of the task at hand. Behavioral studies have shown that distractors cause less interference when the attentional demands (perceptual load) of a task increase (Lavie and Tsal, 1994; Lavie, 1995). The perceptual load theory of attention proposes that such distractor filtering occurs because available attentional resources are diverted from distractor processing and allotted to performance of an attentionally demanding task (Lavie and Tsal, 1994; Lavie, 1995). Neurophysiological studies have supported the theory's general propositions, demonstrating that high perceptual load attenuates visual cortical responses to extraneous distractor stimuli (Kramer et al., 1988; Rees et al., 1997; Handy and Mangun, 2000; Handy et al., 2001; Berman and Colby, 2002; Pinsk et al., 2004; Schwartz et al., 2005; Rorden et al., 2008; Rauss et al., 2009, 2012; Parks et al., 2011). Despite these neurophysiological studies, perceptual load theory has not specified the neural substrate that underlies the induction of distractor filtering.

Torralbo and Beck (2008) have described a candidate neural mechanism of perceptual load, proposing that load-induced distractor filtering is a consequence of a top–down biasing signal initiated by the need to resolve neural competition between local representations in visual cortices. These competitive interactions have also been referred to as surround suppression; that is, stimuli are not processed independently but are influenced (suppressed) by surrounding stimuli (Blakemore and Tobin, 1972; Snowden et al., 1991; Knierim and Van Essen, 1992; Miller et al., 1993; Kastner et al., 1998, 2001; Reynolds et al., 1999; Bair et al., 2003). In keeping with such suppressive interactions, the presence of nearby stimuli can impair performance on a variety of tasks (Cave and Zimmerman, 1997; Bahcall and Kowler, 1999; Mounts, 2000; Kristjánsson et al., 2002; McCarley et al., 2004; Alvarez and Franconeri, 2007; Shim et al., 2008; Hilimire et al., 2009; Franconeri et al., 2010; Chan and Hayward, 2012). Top–down attention, however, serves to isolate the attended items from their surround (Moran and Desimone, 1985; Luck et al., 1997; Recanzone et al., 1997; Kastner et al., 1998; Reynolds et al., 1999; Recanzone and Wurtz, 2000; Sundberg et al., 2009) that is, the influence of the unattended stimuli is suppressed. According to biased competition theory (Reynolds et al., 1999) and normalization models of attention (Reynolds and Heeger, 2009), the suppression of unattended stimuli is a natural consequence of the inherent inhibitory interactions in visual cortex. By enhancing a target, competitively connected surrounding stimuli will necessarily be suppressed. Such models make two predictions. First, the degree of target enhancement will determine the degree of distractor suppression; in other words, if increasing the load of a task results in a need for greater enhancement of the target this should be accompanied by, as perceptual load theory predicts, greater suppression of unattended stimuli. Second, if local competitive interactions underlie load-dependent suppression then suppression should be greatest for distractor locations that are more likely to share local inhibitory interactions with the attended stimulus; that is, distractor locations most proximal to the attended target should be suppressed more than those that are more distant.

Here, we examined the spatial distribution of load-dependent enhancement and distractor suppression by parametrically manipulating distractor eccentricity during performance of a foveal visual discrimination task that varied between low and high perceptual load. Frequency-domain steady-state visual evoked potentials (SSVEPs) were measured in response to peripheral distractor stimuli and were used to evaluate distractor suppression (Müller et al., 1998a,b; Müller and Hübner, 2002; Müller and Kleinschmidt, 2003; Keitel et al., 2010; Parks et al., 2011). Time-domain event-related potentials (ERPs) were also recorded in response to task-relevant foveal stimuli and were used to evaluate attentional modulation of foveal visual processing. In accordance with Torralbo and Beck (2008) and the predictions of biased competition and normalization theories, we predicted that foveal perceptual load should result in an enhanced visual response to foveal stimuli but that this enhancement should also be associated with increased distractor suppression (filtering). Furthermore, as predicted by biased competition and normalization theory, this increased suppressive drive should be strongest at spatial locations most proximal to the attentionally demanding stimulus (i.e., foveal target). As such, we predicted that foveal load should produce the strongest suppression at the most proximal distractor locations.

METHOD

SUBJECTS

Twenty subjects (11 females, mean age = 21.5 years) were recruited from the University of Illinois Urbana-Champaign. All subjects reported normal or corrected to normal vision. Written informed consent was obtained prior to experimentation. All procedures were approved by the University of Illinois Institutional Review Board. Subjects were paid $10 per hour for their participation in the experiment.

STIMULI AND PROCEDURE

Subjects performed a foveal go/no-go task in the presence of irrelevant distractor rings that contrast reversed at a rate of 8.3 Hz. Trials were 6.0 s in duration. Every 1000–1500 ms of this trial one of four rectangles was flashed at fixation for 100 ms. Rectangles ($1.0 \times 0.5°$) were black or white and oriented either horizontally or vertically. Four such task stimuli were randomly selected and presented during a trial. For a block of trials, two of the four rectangles were assigned as targets. Perceptual load was manipulated between blocks. In Low Load blocks, targets were assigned such that they could be discriminated from non-targets by color alone whereas high load blocks required discrimination of a conjunction of color and orientation (**Figure 1**). For example, in a low load block, targets may be assigned as vertical white and horizontal white rectangles whereas in a high load block targets may be vertical white and horizontal black. High load blocks were expected to be much more attentionally demanding than low load blocks (Treisman and Gelade, 1980). Subjects were instructed to respond to target rectangles as quickly as possible and withhold responses to non-target rectangles. This go/no-go task was performed in isolation or in the context of peripheral checkerboard rings. Peripheral ring stimuli consisted of one of three rings positioned at eccentricities of 2, 6, or 11° from fixation. Ring size was scaled for cortical magnification according to the method described in Carrasco and Frieder (1997). Rings contrast reversed at 8.3 Hz for the entirety of the 6.0 s trial. Peripheral rings were irrelevant to the central go/no-go task and subjects were instructed to ignore them.

Subjects completed four practice blocks of four trials followed by eight blocks of 40 trials, each 6 s in duration. The order of perceptual load conditions was counterbalanced between subjects. Within a block there was an equal weighting of peripheral distractor trial types (2, 6, 11°, and no-distractor). Time-domain ERPs were measured in response to go/no-go task stimuli and frequency-domain SSVEPs were measured in response to peripheral contrast-reversing rings.

EEG RECORDING AND ANALYSIS

Electroencephalogram (EEG) was recorded from 30 Ag-AgCl scalp electrodes with a Synamps 2 amplifier (Neuroscan, El Paso, TX). Electrodes were positioned according to the modified 10–20 system at the following locations: O1, Oz, O2, P7, P3, Pz, P4, P8, TP7, CP3, CPz, CP4, TP8, T7, C3, Cz, C4, T8, FT7, FC3, FCz, FC4, FT8, F7, F3, Fz, F4, F8. Vertical electrooculogram (VEOG) and horizontal electrooculogram (HEOG) were formed from bipolar channels calculated from electrodes positioned above and below the left eye and on the outer canthi of the left and right eye. EEG was referenced to right mastoid, sampled at 1000 Hz, and bandpass filtered from 0.1 to 40 Hz. Offline, data were re-referenced to the average of the two mastoid channels. Electrodes were selected for analysis based on previous literature and grand average scalp distributions across all conditions. ANOVAs with more than 2°

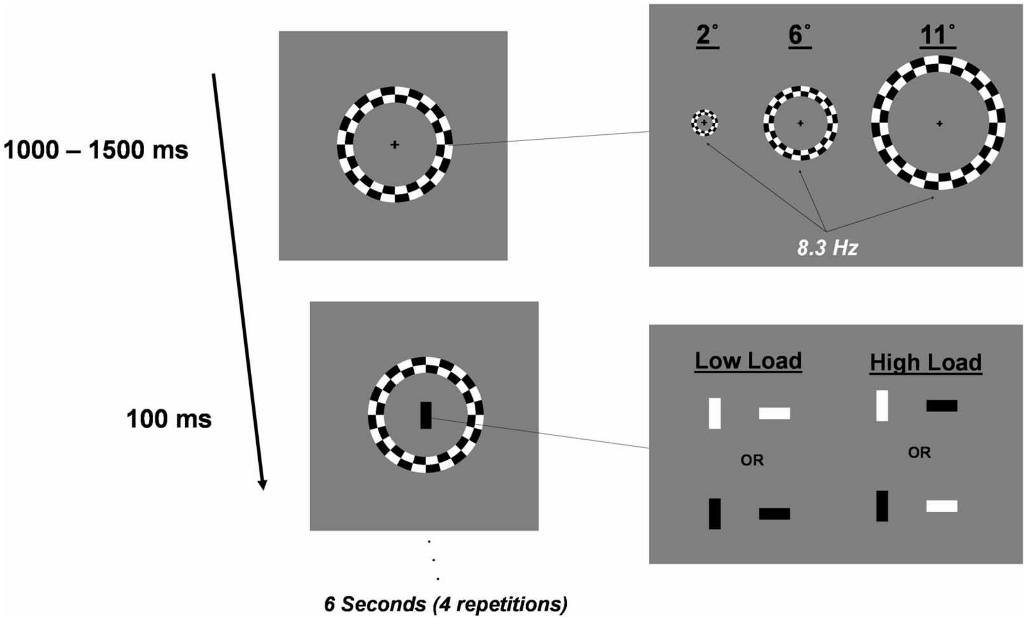

FIGURE 1 | Schematic representation of stimuli and trial progression. Distractor stimuli were one of three rings centered at 2, 6, or 11° from fixation. Distractor stimuli contrast reversed at 8.3 Hz. Foveal stimuli were black or white rectangles oriented vertically or horizontally. Subjects performed a go/no-go task, responding to two targets that were assigned for a block of trials. Trials length was 6.0 s. Distractors contrast-reversed for the duration of the trial. Task stimuli were presented randomly every 1000–1500 ms. Four task stimuli occurred during each 6.0 s trial and were randomly selected (with replacement) from the four possible go/no-go task stimuli.

in the numerator were corrected for sphericity using a Huynh-Feldt correction. An alpha level of 0.05 was used as the criteria for significance for all statistical tests.

SSVEPs

For steady-state data, EEG was epoched into segments of 4096 ms, beginning 1500 ms into the trial. This time window was chosen as visual responses to contrast reversing stimuli would have achieved a steady-state, it ensured the presentation of a central task-relevant stimulus, and provided a power of two number of data points (4096) necessary for the fast Fourier transform (FFT) algorithm. Individual segments were detrended and baseline corrected over the 4096 ms interval. Segments were considered artifacts and rejected from analysis if activity in any scalp or EOG channel exceeded ±80 μV. Segmented data were then time averaged separately for each condition of load and ring eccentricity. Frequency-domain signals (8.3 Hz) were extracted by submitting time-averaged data to FFT (10% Hanning window). 8.3 Hz amplitudes were submitted to 3 × 2 × 3 repeated measures ANOVA with factors of electrode (O1, Oz, or O2), load (low load or high load), and eccentricity (2, 6, or 11° rings).

ERPs

Time-domain ERPs to task-relevant stimuli at fixation were calculated by averaging 700 ms segments of EEG time-locked to each stimulus presentation. Individual segments were rejected from analysis if activity exceeded ±80 μV. Segmented data were averaged separately for low load and high load conditions. Visual sensory components, P1 and N1, were selected a priori for statistical analysis. Mean amplitudes within 110–150 and 175–210 ms time windows were used to quantify P1 and N1 amplitudes, respectively. P1 and N1 amplitudes were submitted to separate repeated measures ANOVAs with factors of electrode (P7 or P8), load (low or high load), and distractor type (2, 6, or 11°, or no distractor).

RESULTS

BEHAVIORAL PERFORMANCE

Consistent with the increased attentional demands of high attentional load blocks, responses to target stimuli appearing at fixation were faster and more accurate under low load than high load. Paired samples *t*-tests were used to test behavioral differences between low and high load performance. Reaction times were faster under low attentional load, $t_{(19)} = -23.59$, $p < 0.001$ (low load: $M = 371$ ms, $SD = 41$ ms; high load: $M = 526$ ms, $SD = 52$ ms). Subjects were also more accurate under low load, $t_{(19)} = 4.03$, $p < 0.001$ (low load: $M = 0.993$, $SD = 0.020$; high load: $M = 0.970$, $SD = 0.041$).

FREQUENCY-DOMAIN SSVEPs

A significant electrode × load × eccentricity interaction was found for 8.3 Hz steady-state amplitudes, $F_{(4, 76)} = 2.93$, $\varepsilon = 0.708$, $p = 0.045$. Follow-up ANOVAs were performed at each electrode and revealed significant load × eccentricity interactions at Oz, $F_{(2, 38)} = 4.01$, $\varepsilon = 0.675$, $p = 0.045$, and O2, $F_{(2, 38)} = 4.99$, $\varepsilon = 0.722$, $p = 0.023$. Paired-samples *t*-tests comparing differences between low and high load at each eccentricity revealed that distractor SSVEPs were attenuated under high load at the most proximal eccentricity (2°), Oz: $t_{(19)} = 3.09$, $p = 0.006$, and O2: $t_{(19)} = 3.51$, $p = 0.002$. No differences due to load were present for rings at 6 or 11° eccentricities (all p's >0.28). Grand average time-domain visual responses from SSVEP trials are plotted for each eccentricity in **Figure 2**. Grand average scalp distribution and load-dependent SSVEP amplitudes for each eccentricity are plotted in **Figure 3A**.

TIME-DOMAIN ERPs

Analysis of P1 amplitudes revealed a main effect of distractor type, $F_{(3.57)} = 10.61$, $\varepsilon = 0.863$, $p < 0.001$, but no significant effects of attentional load (all p's > 0.07). The main effect of distractor type resulted from increased P1 amplitude with increasing eccentricity of peripheral distractors (or their absence), supported by mean P1 amplitudes across conditions of distractor type (2°: $M = 1.31\,\mu$V, $SD = 1.00\,\mu$V; 6°: $M = 1.59\,\mu$V, $SD = 1.12\,\mu$V; 11°: $M = 1.73\,\mu$V, $SD = 1.26\,\mu$V; no distractor: $M = 2.15\,\mu$V, $SD = 1.40\,\mu$V) and a significant linear trend of distractor type, $F_{(1,\ 19)} = 30.17$, $p < 0.001$. This relationship between P1 suppression and distractor proximity may reflect visual competition between task-relevant foveal stimuli and peripheral distractors, as described previously by Parks et al. (2011). However, this result will not be interpreted further as investigating such an effect was not a goal of the present experiment nor was there interaction with attentional load.

The N1 ANOVA revealed a significant main effect of load, $F_{(1,\ 19)} = 45.94$, $p < 0.001$ resulting from greater N1 amplitude under high attentional load relative to low. Grand average time-domain ERPs and scalp distribution are plotted in **Figure 3B**.

DISCUSSION

The perceptual load theory of attention proposes that irrelevant or distracting stimuli become filtered as the attentional demands of a task increase (Lavie and Tsal, 1994; Lavie, 1995). Though the theory does not specify a neural mechanism of these effects, Torralbo and Beck (2008) have proposed that such perceptual load is a consequence of a top–down biasing signal being driven by neural competition. This proposal, in conjunction with the predictions of biased competition and normalization theories of attentions, predicts that stimulus locations rendered high in perceptual load will result in a neural enhancement of the attentionally demanding stimulus while simultaneously inducing a region of visual suppression in spatially proximal locations. We used time-domain ERPs together with frequency-domain SSVEPs to test this proposition by examining load-dependent enhancement and suppression in the visual field.

Time-domain ERPs elicited by foveal task-relevant stimuli revealed evidence of enhanced visual processing under high perceptual load. Specifically, amplitude of the posterior N1 component was significantly potentiated in the high load condition relative to low. This finding is consistent with several previous

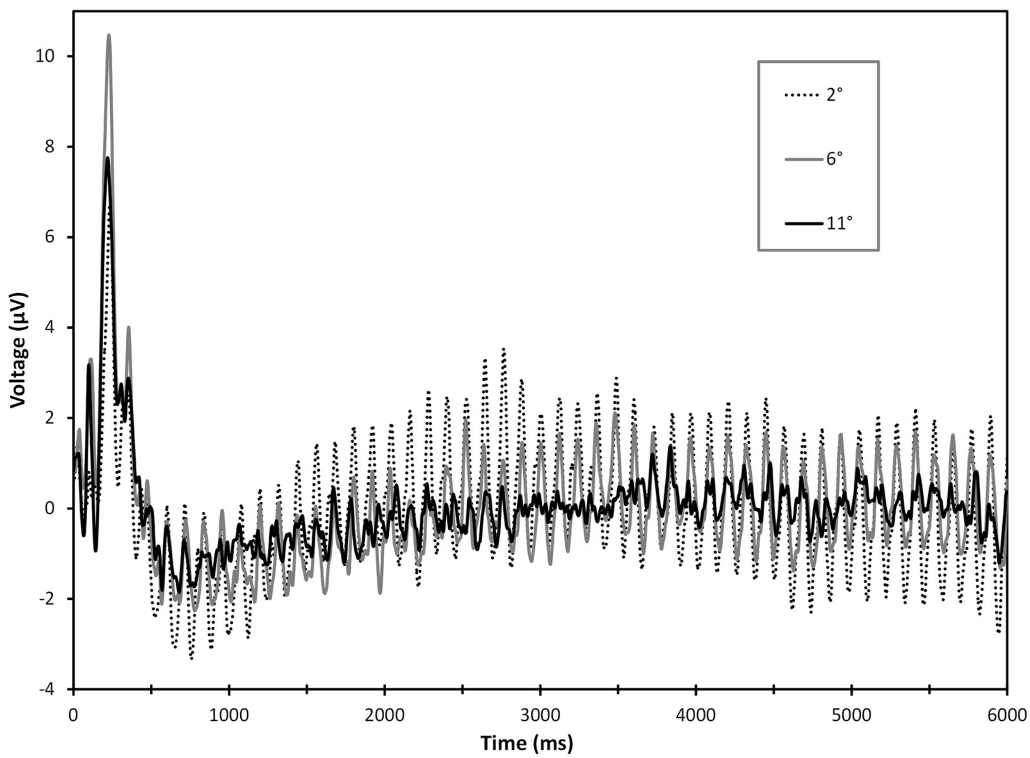

FIGURE 2 | Grand average time-domain responses for 8.3 Hz SSVEP responses over the course of a 6.0 s trial, collapsed across electrodes O1, Oz, and O2. Notice a large initial transient visual response to the onset of peripheral ring distractors followed by entrainment of the steady-state response. Frequency-domain signals of SSVEPs were extracted from a period of 4096 ms beginning 1500 ms into the trial.

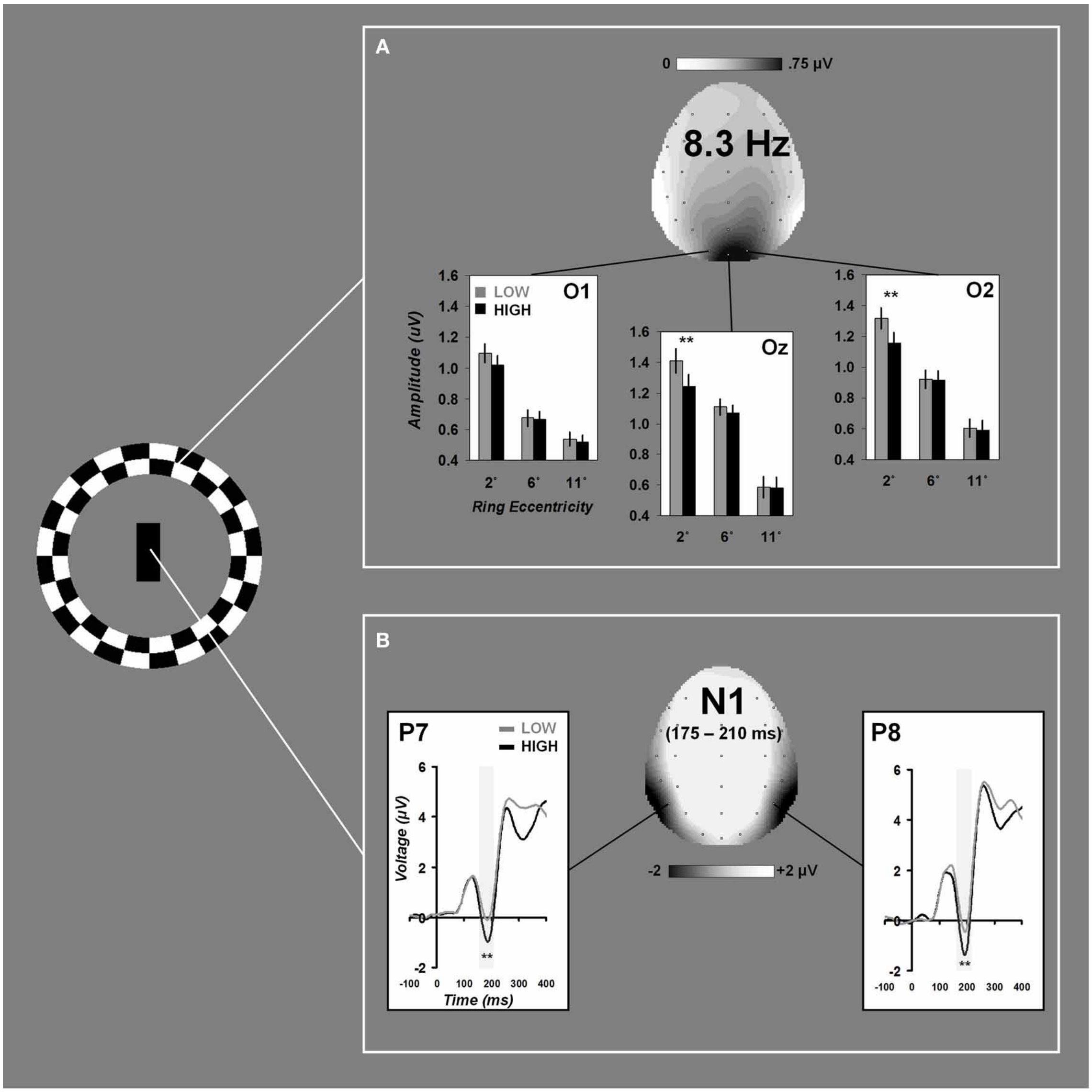

FIGURE 3 | Load-dependent effects on distractor and task-relevant visual processing. Grand average effects of attentional load on 8.3 Hz peripheral distractor amplitudes are plotted for electrodes O1, Oz, and O2 in **(A)**. Grand average time-domain ERPs to foveal task-relevant stimuli at electrodes P7 and P8 are shown in **(B)**. Scalp distributions reflect the grand averages collapsed across all conditions. Error bars represent ±1 SEM.

ERP studies which have reported increased N1 amplitude to high load task-relevant stimuli (Handy and Mangun, 2000; Rorden et al., 2008; Rauss et al., 2009, 2012). The visual posterior N1 has been proposed to reflect processes of stimulus discrimination, as it has been found to increase in amplitude when subject must discriminate stimuli relative to when no discrimination is required (Vogel and Luck, 2000). The N1 modulation observed in our experiment and others (Handy and Mangun, 2000; Rorden et al., 2008; Rauss et al., 2009, 2012) may be related to such a process but our results clearly demonstrate that N1 amplitude modulates with the attentional load of a task. Vogel and Luck (2000) previously tested whether perceptual load could account for discrimination effects in the N1 and found no effect of load. However, their manipulation of perceptual load varied the similarity of color between targets and distractors to influence task difficulty. Such a manipulation may have increased task difficulty through sensory limitations rather than attentional demands, which have been shown to be distinctly different methods of manipulating task difficulty (Lavie and De Fockert, 2003).

A potential alternative interpretation of the load-dependent N1 modulation reported here is that it result from differential attentional capture between high and low load conditions (Folk et al., 1992; Fuchs and Ansorge, 2012; Fuchs et al., 2013). In the high load condition, every no-go stimulus matched the color of one of the assigned targets whereas no-go stimuli in low load never matched the color of assigned targets. As such, no-go stimuli in the high load condition may have induced attentional capture by color whereas no-go stimuli in the low load condition may not induce such capture. This imbalance of attentional capture between low and high load conditions could potentially have led to a load-dependent modulation of the N1 modulation. Such an interpretation cannot be ruled out in the present experiment as the increased attentional demands of the high load condition predict an effect in the same direction (i.e., modulation of visual sensory components). However, previous studies of attentional load have also described such an N1 effect but have used manipulations that do not differentially influence attentional capture (Rorden et al., 2008; Rauss et al., 2009, 2012). We propose that the increased N1 reported here reflects an enhancement in perceptual processing occurring as a result of the increased attentional demands required under high perceptual load, and potentially mediated by a top–down biasing signal.

Evidence of the suppression of visual distractor stimuli was apparent in 8.3 Hz distractor SSVEPs. Parametric manipulation of distractor eccentricity revealed that high central load attenuated 8.3 Hz distractor signals at the most proximal position (2° from the task-relevant location). No evidence of load-dependent distractor suppression was apparent at eccentricities beyond 2° (6 or 11°). These findings are consistent with the predictions of surround suppression and biased competition theory (Reynolds et al., 1999) and normalization theory (Reynolds and Heeger, 2009), and demonstrate that increased attentional load at fixation induces a relatively narrow region of distractor suppression surrounding the spatial location with increased attentional demand, rather than inducing uniform filtering of distractor stimuli throughout the visual field.

Our SSVEP results showed the strongest suppression at the spatial position nearby the attentionally demanding central load task but did not reveal significant suppression at further distances. However, previous psychophysical and neuroimaging data have shown evidence of load-dependent visual suppression at eccentricities beyond 10°. Plainis et al. (2001) previously reported increased visual detection thresholds in a foveal load task for spatial locations up to 10° from fixation but significantly less suppression for eccentricities beyond 10°. However, these results were based on behavioral responses rather than neurophysiological recordings and the use of a secondary psychophysical task for threshold measurement was likely to have influenced subjects' attentional strategies and, in turn, the measured spatial configuration of distractor suppression. Some neurophysiological data have also indicated that load-induced visual suppression is measurable at distant eccentricities. A previous fMRI study by Schwartz et al. (2005) found some load-dependent suppression within retinotopically-organized cortex presumed to represent eccentricities beyond those reported here (>2°). However, in their fMRI study, distractor stimuli were near full-hemifield checkerboard wedges. Object-based and space-based mechanisms of attention have been shown to interact such that spatial effects can "spread" within an object's spatial boundaries and retinotopic representations (Vecera and Farah, 1994; Kramer et al., 1997; Müller and Kleinschmidt, 2003). If the large distractor stimulus used by Schwartz et al. was grouped as an object, it is possible that distractor suppression spread from less eccentric to more eccentric representations. Furthermore, Schwartz et al. extracted eccentricity information from fMRI activations obtained in retinotopic mapping scans of visual cortical areas, which did not discretize comparisons of load effects across the visual field. The present study placed discrete objects (checkerboard rings) at known eccentricities, minimizing any potential space-object interactions and avoiding interpretation issues associated with retinotopic extraction of cortical representations of eccentricity. Though our parametric manipulation of eccentricity provides a straightforward method of examining load-dependent modulations across visual space, it could be argued that overall differences in SSVEP amplitude between 2, 6, and 11° distractors negatively impacted our ability to detect attentional effects, as SSVEP signals progressively decreased in amplitude from 2, 6, and 11°, despite scaling ring size for cortical magnification (**Figures 2**, **3A**). Although we cannot completely rule out that we simply were unable to measure more peripheral effects of attention, we do not believe the SSVEP amplitude differences to be of major concern as all eccentricities exhibited a robust 8.3 Hz signal and even the most eccentric position in our experiment (11°) exhibited an average frequency-domain amplitude greater than 0.5 μV, a value comparable to signals of previous studies of spatial attention using SSVEPs (Müller et al., 1998a,b, 2003; Müller and Hübner, 2002). Though the existence of a diminutive effect of perceptual load at more peripheral locations remains a possibility, our SSVEP data clearly indicate that load-dependent visual suppression has the most pronounced effects in the regions of visual space directly surrounding task-relevant stimuli.

Together, results from time-domain ERPs and frequency-domain SSVEPs indicate that attentional load induces a center-surround configuration of facilitation and suppression in the visual field. Specifically, enhancement of perceptual-level processing was present at the central task-relevant location (load-dependent N1 effect) whereas suppression was apparent only in a region of space surrounding this location (2° load-dependent SSVEP effect). Such a configuration is in accordance with predictions from normalization theory of attention, with the simple assumption that the "suppressive drive" of a neuron is spatially restricted at least in early to intermediate levels of visual cortex (Reynolds and Heeger, 2009) and is further consistent with previously reported findings of a center-surround distribution of *spatial* selective attention to peripheral locations (Müller and Kleinschmidt, 2004; Müller et al., 2005; Hopf et al., 2006; Boehler et al., 2009). Though the present results demonstrate a center-surround distribution they provide a relatively crude resolution of measurement, as load-dependent comparisons were made 2, 6, and 11° from fixation using stimuli scaled for cortical magnification. It is possible that taking finer-resolution measurements between 2 and 6° could reveal a more complex configuration of facilitation and suppression. Furthermore, it remains unclear whether the present results reflect a static configuration where suppression always occurs at predetermined regions of the visual field, or a dynamic center-surround configuration that scales according to the attended region of space (e.g., Reynolds and Heeger, 2009). For example, if the task-relevant location encompassed an area 3°

in diameter, the relative distribution of facilitation and suppression may be predicted to scale accordingly. The aforementioned possibilities can only be addressed with, potentially through further experimentation with an adapted version of the paradigm used here.

A recent set of studies has called into question the validity of perceptual load theory [Benoni and Tsal, 2010, 2012; Tsal and Benoni, 2010a,b however, see Lavie and Torralbo (2010)] and should be discussed in the context of the current experiment. Dilution theory purports that the described effects of perceptual load in search displays are not due to increased attentional distractor suppression but are due to the dilution of distractor items by a large number of neutral items. The present study used identical stimuli between low and high load conditions and manipulated attentional demands through the task performed on those stimuli (i.e., targets were assigned by color or by color/orientation). As there were no stimulus differences between the configuration of low load and high load displays, dilution cannot account for our findings of central visual enhancement and suppression by load. The intention of our study was not to directly compare perceptual load and dilution theories. However, the load-dependent ERP and SSVEP effects described here are clearly the result of the attentional demands induced by the central load task rather than an effect of dilution by distractor items.

In summary, our results demonstrate that load-dependent distractor filtering assumes a center-surround configuration. Time-domain ERPs and frequency-domain SSVEPs revealed that, under conditions of high perceptual load, visual processing is enhanced at a task-relevant location but is suppressed in the space immediately surrounding that location.

REFERENCES

Alvarez, G. A., and Franconeri, S. L. (2007). How many objects can you track?: evidence for a resource-limited attentive tracking mechanism. *J. Vis.* 7, 14.1–14.10.

Bahcall, D. O., and Kowler, E. (1999). Attentional interference at small spatial separations. *Vision Res.* 39, 71–86.

Bair, W., Cavanaugh, J. R., and Movshon, J. A. (2003). Time course and time-distance relationships for surround suppression in macaque V1 neurons. *J. Neurosci.* 23, 7690–7701.

Benoni, H., and Tsal, Y. (2010). Where have we gone wrong? Perceptual load does not affect selective attention. *Vision Res.* 50, 1292–1298.

Benoni, H., and Tsal, Y. (2012). Controlling for dilution while manipulating load: perceptual and sensory limitations are just two aspects of task difficulty. *Psychon. Bull. Rev.* 19, 631–638.

Berman, R. A., and Colby, C. L. (2002). Auditory and visual attention modulate motion processing in area MT+. *Cogn. Brain Res.* 14, 64–74.

Blakemore, C., and Tobin, E. A. (1972). Lateral inhibition between orientation detectors in the cat's visual cortex. *Exp. Brain Res.* 15, 439–440.

Boehler, C. N., Tsotsos, J. K., Schoenfeld, M. A., Heinze, H. J., and Hopf, J. M. (2009). The center-surround profile of the focus of attention arises from recurrent processing in visual cortex. *Cereb. Cortex* 19, 982–991.

Carrasco, M., and Frieder, K. S. (1997). Cortical magnification neutralizes the eccentricity effect in visual search. *Vision Res.* 37, 63–82.

Carrasco, M., Ling, S., and Read, S. (2004). Attention alters appearance. *Nat. Neurosci.* 7, 308–313.

Cave, K. R., and Zimmerman, J. M. (1997). Flexibility in spatial attention before and after practice. *Psychol. Sci.* 8, 399–403.

Chan, L. K., and Hayward, W. G. (2012). Dimension-specific signal modulation in visual search: evidence from inter-stimulus surround suppression. *J. Vis.* 12, 1–10.

Folk, C. L., Remington, R. W., and Johnston, J. C. (1992). Involuntary covert orienting is contingent on attentional control settings. *J. Exp. Psychol. Hum. Percept. Perform.* 18, 1030–1044.

Franconeri, S. L., Jonathan, S. V., and Scimeca, J. M. (2010). Tracking multiple objects is limited only by object spacing, not by speed, time, or capacity. *Psychol. Sci.* 21, 920–925.

Fuchs, I., and Ansorge, U. (2012). Inhibition of return is no hallmark of exogenous capture by unconscious cues. *Front. Hum. Neurosci.* 6:30. doi: 10.3389/fnhum.2012.00030

Fuchs, I., Theeuwes, J., and Ansorge, U. (2013). Exogenous attentional capture by subliminal abrupt-onset cues: evidence from contrast-polarity independent cueing effects. *J. Exp. Psychol. Hum. Percept. Perform.* doi: 10.1037/a0030419. [Epub ahead of print].

Handy, T. C., and Mangun, G. R. (2000). Attention and spatial selection: electrophysiological evidence for modulation by perceptual load. *Attent. Percept. Psychophys.* 62, 175–186.

Handy, T. C., Soltani, M., and Mangun, G. R. (2001). Perceptual load and visuocortical processing: event-related potentials reveal sensory-level selection. *Psychol. Sci.* 12, 213–218.

Hilimire, M. R., Mounts, J. R., Parks, N. A., and Corballis, P. M. (2009). Competitive interaction degrades target selection: an ERP study. *Psychophysiology* 46, 1080–1089.

Hopf, J. M., Boehler, C. N., Luck, S. J., Tsotsos, J. K., Heinze, H. J., and Schoenfeld, M. A. (2006). Direct neurophysiological evidence for spatial suppression surrounding the focus of attention in vision. *Proc. Natl. Acad. Sci. U.S.A.* 103, 1053–1058.

Kastner, S., De Weerd, P., Desimone, R., and Ungerleider, L. G. (1998). Mechanisms of directed attention in the human extrastriate cortex as revealed by functional MRI. *Science* 282, 108–111.

Kastner, S., De Weerd, P., Pinsk, M. A., Elizondo, M. I., Desimone, R., and Ungerleider, L. G. (2001). Modulation of sensory suppression: implications for receptive fields sizes in the human visual cortex. *J. Neurophysiol.* 86, 1398–1411.

Keitel, C., Andersen, S. K., and Müller, M. M. (2010). Competitive effects on steady-state visual evoked potentials with frequencies in-and outside the alpha band. *Exp. Brain Res.* 205, 489–495.

Knierim, J. J., and Van Essen, D. C. (1992). Neuronal responses to static texture patterns in area V1 of the alert macaque monkey. *J. Neurophysiol.* 67, 961–980.

Kramer, A. F., Sirevaag, E. J., and Hughes, P. R. (1988). Effects of foveal task load on visual spatial attention: event-related brain potentials and performance. *Psychophysiology* 25, 512–531.

Kramer, A. F., Weber, T. A., and Watson, S. E. (1997). Object-based attentional selection—Grouped arrays or spatially invariant representations?: comment on Vecera and Farah (1994). *J. Exp. Psychol. Gen.* 126, 3–13.

Kristjánsson, Á., Wang, D., and Nakayama, K. (2002). The role of priming in conjunctive visual search. *Cognition* 85, 37–52.

Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. *J. Exp. Psychol. Hum. Percept. Perform.* 21, 451.

Lavie, N., and De Fockert, J. W. (2003). Contrasting effects of sensory limits and capacity limits in visual selective attention. *Attent. Percept. Psychophys.* 65, 202–212.

Lavie, N., and Torralbo, A. (2010). Dilution: a theoretical burden or just load? A reply to Tsal and Benoni (2010). *J. Exp. Psychol. Hum. Percept. Perform.* 36, 1657–1664.

Lavie, N., and Tsal, Y. (1994). Perceptual load as a major determinant of the locus of selection in visual attention. *Attent. Percept. Psychophys.* 56, 183–197.

Liu, T., Abrams, J., and Carrasco, M. (2009). Voluntary attention enhances contrast appearance. *Psychol. Sci.* 20, 354–362.

Luck, S. J., Girelli, M., McDermott, M. T., and Ford, M. A. (1997). Bridging the gap between monkey neurophysiology and human perception: an ambiguity resolution theory of visual selective attention. *Cogn. Psychol.* 33, 64–87.

Martinez, A., Anllo-Vento, L., Sereno, M. I., Frank, L. R., Buxton, R. B., Dubowitz, D. J., et al. (1999). Involvement of striate and extrastriate visual cortical areas in spatial attention. *Nat. Neurosci.* 2, 364–369.

McCarley, J. S., Mounts, J. R., and Kramer, A. F. (2004). Age-related differences in localized attentional interference. *Psychol. Aging* 19, 203–210.

Miller, E. K., Gochin, P. M., and Gross, C. G. (1993). Suppression of visual responses of neurons in inferior temporal cortex of the awake macaque by addition of a second stimulus. *Brain Res.* 616, 25–29.

Moran, J., and Desimone, R. (1985). Selective attention gates visual processing in the extrastriate cortex. *Front. Cogn. Neurosci.* 229, 342–345.

Mounts, J. R. (2000). Attentional capture by abrupt onsets and feature singletons produces inhibitory surrounds. *Attent. Percept. Psychophys.* 62, 1485–1493.

Müller, M. M., and Hübner, R. (2002). Can the spotlight of attention be shaped like a doughnut? Evidence from steady-state visual evoked potentials. *Psychol. Sci.* 13, 119–124.

Müller, M. M., Malinowski, P., Gruber, T., and Hillyard, S. A. (2003). Sustained division of the attentional spotlight. *Nature* 424, 309–312.

Müller, M. M., Picton, T. W., Valdes-Sosa, P., Riera, J., Teder-Sälejärvi, W. A., and Hillyard, S. A. (1998a). Effects of spatial selective attention on the steady-state visual evoked potential in the 20-28 Hz range. *Cogn. Brain Res.* 6, 249–262.

Müller, M. M., Teder-Sälejärvi, W., and Hillyard, S. A. (1998b). The time course of cortical facilitation during cued shifts of spatial attention. *Nat. Neurosci.* 1, 631–634.

Müller, N. G., and Kleinschmidt, A. (2003). Dynamic interaction of object-and space-based attention in retinotopic visual areas. *J. Neurosci.* 23, 9812–9816.

Müller, N. G., and Kleinschmidt, A. (2004). The attentional 'spotlight's' penumbra: center-surround modulation in striate cortex. *Neuroreport* 15, 977–980.

Müller, N. G., Mollenhauer, M., Rösler, A., and Kleinschmidt, A. (2005). The attentional field has a Mexican hat distribution. *Vision Res.* 45, 1129–1137.

Parks, N. A., Hilimire, M. R., and Corballis, P. M. (2011). Steady-state signatures of visual perceptual load, multimodal distractor filtering, and neural competition. *J. Cogn. Neurosci.* 23, 1113–1124.

Pinsk, M. A., Doniger, G. M., and Kastner, S. (2004). Push-pull mechanism of selective attention in human extrastriate cortex. *J. Neurophysiol.* 92, 622–629.

Plainis, S., Murray, I. J., and Chauhan, K. (2001). Raised visual detection thresholds depend on the level of complexity of cognitive foveal loading. *Perception* 30, 1203–1212.

Posner, M. I. (1980). Orienting of attention. *Q. J. Exp. Psychol.* 32, 3–25.

Posner, M. I., Snyder, C. R., and Davidson, B. J. (1980). Attention and the detection of signals. *J. Exp. Psychol. Gen.* 109, 160–174.

Prinzmetal, W., Amiri, H., Allen, K., and Edwards, T. (1998). Phenomenology of attention: I. Color, location, orientation, and spatial frequency. *J. Exp. Psychol. Hum. Percept. Perform.* 24, 261.

Prinzmetal, W., Nwachuku, I., Bodanski, L., Blumenfeld, L., and Shimizu, N. (1997). The phenomenology of attention: 2. Brightness and contrast. *Conscious. Cogn.* 6, 372–412.

Rauss, K., Pourtois, G., Vuilleumier, P., and Schwartz, S. (2012). Effects of attentional load on early visual processing depend on stimulus timing. *Hum. Brain Mapp.* 33, 63–74.

Rauss, K. S., Pourtois, G., Vuilleumier, P., and Schwartz, S. (2009). Attentional load modifies early activity in human primary visual cortex. *Hum. Brain Mapp.* 30, 1723–1733.

Recanzone, G. H., and Wurtz, R. H. (2000). Effects of attention on MT and MST neuronal activity during pursuit initiation. *J. Neurophysiol.* 83, 777–790.

Recanzone, G. H., Wurtz, R. H., and Schwarz, U. (1997). Responses of MT and MST neurons to one and two moving objects in the receptive field. *J. Neurophysiol.* 78, 2904–2915.

Rees, G., Frith, C. D., and Lavie, N. (1997). Modulating irrelevant motion perception by varying attentional load in an unrelated task. *Science* 278, 1616–1619.

Reynolds, J. H., Chelazzi, L., and Desimone, R. (1999). Competitive mechanisms subserve attention in macaque areas V2 and V4. *J. Neurosci.* 19, 1736–1753.

Reynolds, J. H., and Heeger, D. J. (2009). The normalization model of attention. *Neuron* 61, 168–185.

Rorden, C., Guerrini, C., Swainson, R., Lazzeri, M., and Baylis, G. C. (2008). Event related potentials reveal that increasing perceptual load leads to increased responses for target stimuli and decreased responses for irrelevant stimuli. *Front. Hum. Neurosci.* 2:4. doi: 10.3389/neuro.09.004.2008

Schwartz, S., Vuilleumier, P., Hutton, C., Maravita, A., Dolan, R. J., and Driver, J. (2005). Attentional load and sensory competition in human vision: modulation of fMRI responses by load at fixation during task-irrelevant stimulation in the peripheral visual field. *Cereb. Cortex* 15, 770–786.

Shim, W. M., Alvarez, G. A., and Jiang, Y. V. (2008). Spatial separation between targets constrains maintenance of attention on multiple objects. *Psychon. Bull. Rev.* 15, 390–397.

Silver, M. A., Ress, D., and Heeger, D. J. (2007). Neural correlates of sustained spatial attention in human early visual cortex. *J. Neurophysiol.* 97, 229–237.

Snowden, R. J., Treue, S., Erickson, R. G., and Andersen, R. A. (1991). The response of area MT and V1 neurons to transparent motion. *J. Neurosci.* 11, 2768–2785.

Sundberg, K. A., Mitchell, J. F., and Reynolds, J. H. (2009). Spatial attention modulates center-surround interactions in macaque visual area V4. *Neuron* 61, 952–963.

Torralbo, A., and Beck, D. M. (2008). Perceptual-load-induced selection as a result of local competitive interactions in visual cortex. *Psychol. Sci.* 19, 1045–1050.

Treisman, A. M., and Gelade, G. (1980). A feature-integration theory of attention. *Cogn. Psychol.* 12, 97–136.

Tsal, Y., and Benoni, H. (2010a). Diluting the burden of load: perceptual load effects are simply dilution effects. *J. Exp. Psychol. Hum. Percept. Perform.* 36, 1645–1656.

Tsal, Y., and Benoni, H. (2010). Much dilution little load in Lavie, and Torralbo's, (2010b) response: a reply. *J. Exp. Psychol. Hum. Percept. Perform.* 36, 1665–1668.

Vecera, S. P., and Farah, M. J. (1994). Does visual attention select objects or locations? *J. Exp. Psychol. Gen.* 123, 146–160.

Vogel, E. K., and Luck, S. J. (2000). The visual N1 component as an index of a discrimination process. *Psychophysiology* 37, 190–203.

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Attentional load and attentional boost: a review of data and theory

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Both perceptual and cognitive processes are limited in capacity. As a result, attention is selective, prioritizing items and tasks that are important for adaptive behavior. However, a number of recent behavioral and neuroimaging studies suggest that, at least under some circumstances, increasing attention to one task can enhance performance in a second task (e.g., the attentional boost effect). Here we review these findings and suggest a new theoretical framework, the dual-task interaction model, that integrates these findings with current views of attentional selection. To reconcile the attentional boost effect with the effects of attentional load, we suggest that temporal selection results in a temporally specific enhancement across modalities, tasks, and spatial locations. Moreover, the effects of temporal selection may be best observed when the attentional system is optimally tuned to the temporal dynamics of incoming stimuli. Several avenues of research motivated by the dual-task interaction model are then discussed.

Keywords: attention, temporal selection, dual-task interference, attentional boost effect, load theory

Even the earliest writings on attention indicate that it is both limited in capacity and selective in nature (James, 1890; Johnston and Dark, 1986). Since then, extensive controversy has surrounded the nature of those limits and the processing stage at which they occur (Pashler, 1994; Driver, 2001). In all of this, however, few studies challenge the idea that attentional capacity is limited. Increasing attention to one task almost always impairs, or at best has no effect on, performance on a second task (Kinchla, 1992). In contrast to these findings, however, a number of recent reports suggest that transient increases in attention to one task can boost performance in a second encoding task (Lin et al., 2010; Swallow and Jiang, 2010). In this review, we briefly present an influential view of attentional selection (Lavie and Tsal, 1994; Lavie, 2005) that is based on the assumptions that perceptual and cognitive resources are limited. We then review recent findings that challenge these assumptions by demonstrating that increasing attention to one task can sometimes enhance performance in a second task. We propose a new model to account for how a limited-capacity system like attention produces these enhancements.

LOAD AND SELECTION

Because attention is limited in capacity (Kinchla, 1992), one must prioritize behaviorally relevant items to ensure that they drive task performance. For decades, attention research has sought to place selective attention within the broader perceptual and cognitive framework (Pashler, 1998). *Early selection* theories (e.g., Broadbent, 1958) suggest that attention acts as a perceptual filter, preventing the identification and semantic analysis of unattended sensory information. *Late selection* theories (e.g., Deutsch and Deutsch, 1963; Duncan, 1980) suggest that selection occurs after sensory stimuli have been identified but before they reach awareness.

The load theory of attentional selection (Lavie and Tsal, 1994; Lavie, 1995; Lavie et al., 2004) reconciled these views by suggesting that attentional selection occurs both early and late in processing, but that early selection varies according to the perceptual and cognitive demands of the attended stimuli. Load theory originated from combining two influential ideas: that attention has limited-capacity (Kahneman, 1973), and that all available perceptual resources will be obligatorily used to process sensory input (Treisman, 1969). This combination leads load theory to two assertions.

First, because perceptual resources are used obligatorily, the upper limit to perceptual processing is also its lower limit. Control processes first direct perceptual resources to goal-relevant (attended) stimuli. Any remaining resources will spill over to irrelevant (unattended) stimuli. As a result, if an attended item (target) requires few perceptual resources to process and identify, then the remaining perceptual resources will "spill over" to process unattended (distractor) stimuli. Late selection then reduces the effect of these irrelevant items on behavior. In contrast, if an attended item requires more perceptual resources, then fewer should spill over to unattended items. Early selection occurs under these circumstances because irrelevant items undergo little perceptual processing. Several factors influence the amount of resources that are needed to perceive an attended item, including the number of distractors (set size), the perceptual similarity between targets and distractors, and stimulus quality (e.g., whether it has been degraded; Lavie and Tsal, 1994; Lavie, 2005).

Evidence for the assertion that excess perceptual resources spill over to distractors came from studies that used the Eriksen flanker paradigm (e.g., Lavie, 1995). Participants indicated which of two-target letters (e.g., a Z or an X) was presented in a central region of the screen. Letters presented in the periphery were task-irrelevant but were associated with a response that was the same as (congruent) or different than (incongruent) the response to the central letter. When the central region contained few letters (low perceptual load), the irrelevant peripheral letter influenced performance, and produced a congruency effect. In contrast, when more letters were present and perceptual load was high, the irrelevant letter's influence on performance was substantially reduced. This pattern of data has been replicated in studies using other manipulations of perceptual load, including those that increase load by requiring conjunction, rather than feature search, and by degrading the perceptual quality of the stimuli (Lavie, 2005). Moreover, increasing perceptual load decreases the response of brain regions involved in processing task-irrelevant stimuli (e.g., Yi et al., 2004; Bahrami et al., 2007).

A second assertion of load theory accounts for the effects of irrelevant items on task performance (Lavie et al., 2004). Because control processes direct perceptual resources to attended stimuli, any manipulations that impair control processes will disrupt their ability to do so. Therefore, increasing demands on control processes should impair selection, increasing the likelihood that irrelevant items will influence performance. This prediction was confirmed when the low perceptual load condition used in earlier studies was combined with a working memory task (Lavie et al., 2004): The effects of an irrelevant item on task performance were stronger when six items were maintained in memory, rather than one. Importantly, manipulations of cognitive load only affect the processing of irrelevant items when they conflict with relevant items (e.g., both involve spatial processing; de Fockert et al., 2001; Carmel et al., 2012).

Although it is not without controversy (Lavie and Torralbo, 2010; Tsal and Benoni, 2010; Wilson et al., 2011), load theory can account for a large amount of data (Lavie and Tsal, 1994; Lavie, 2005), and encompasses processes that occur throughout task performance. Like other accounts of attention and control, load theory focuses on capacity limitations, both in perception and in control. Here we review evidence that challenges the ubiquity of these limitations, demonstrating that increasing attention to one task can sometimes enhance performance in another task (Lin et al., 2010; Swallow and Jiang, 2010; Swallow et al., 2012).

DETECTING A TARGET FOR ONE TASK BROADLY ENHANCES PERCEPTUAL PROCESSING

Behaviorally relevant or novel events often signal the need to adapt one's goals and activities to a new context. In everyday life, such events might constitute a knock at the door, an email notification, or the appearance of a friend one has been waiting for. In the lab, behaviorally relevant events are often pre-defined targets to which participants have been instructed to respond[1]. In all cases, selective attention is needed to identify the stimulus and determine an appropriate response (Chun and Potter, 1995; Nieuwenhuis et al., 2005). Perhaps less obviously, because these events represent a change in the current situation, they may also lead to enhanced perceptual processing of their broader context (Donchin and Coles, 1988; Chun and Jiang, 1998; Bouret and Sara, 2005; Zacks et al., 2007). Consistent with this possibility, extensive data indicate that perceptual and conceptual information that is present when observed activities change form an important component of long-term episodic memory (Newtson and Engquist, 1976; Hanson and Hirst, 1989; Lassiter and Slaw, 1991; Schwan and Garsoffky, 2004; Swallow et al., 2009). However, these data apply almost exclusively to changes in observed activities, rather than to situations in which an event cues an observer to act. Whereas increased attention to context may be expected when activities change, load theory (Lavie, 2005) suggests that increasing attention to a relevant item should decrease the processing of concurrent perceptual information.

The limited-capacity of perceptual processing and attention (Lavie, 2005) necessitates that attending to a relevant event, such as a target, decreases attention to unrelated information that coincides with it. Indeed, most of what is understood about attention predicts that attending to a target should impair, rather than enhance, the processing of concurrently presented but unrelated information. For example, in the attentional blink, participants are typically asked to report the identity of two-target letters that appear in a stream of distractors (Raymond et al., 1992; Chun and Potter, 1995; Dux and Marois, 2009). Items are presented quickly, often at a rate of 10 per second, making their identification difficult. Detecting the first target in the stream reduces the ability to report the identity of the second target when it appears approximately 200–500 ms later. Similarly, in the two-target cost, Duncan (1980) demonstrated that the ability to detect a target is impaired when it coincides with another target, rather than a distractor. Thus, relative to distractor rejection, detecting and responding to a target produces significant demands on attention that reduce the availability of attentional resources for other items.

Over the last several years, however, several studies have presented data that seemingly challenge the ubiquity of interference from target detection. Data from multiple sources, including studies of memory, priming, brain activity, and perceptual learning suggest that attending to a behaviorally relevant target item can actually boost the perceptual processing of concurrent, but unrelated information.

In one study, Swallow and Jiang (2010) asked participants to perform two continuous tasks at the same time (**Figure 1A**). For one task participants were shown a series of scenes, one at a time (500 ms/item), at the center of the screen. Participants encoded all of the scenes for a subsequent memory test. For a second task a stream of squares was presented at fixation (also 500 ms/item). The square could be black or white, and participants pressed a key as quickly as possible whenever a white target square appeared. Importantly, the square was completely unrelated to the scene. To examine the effect of target squares on encoding the background scenes, the scenes were assigned to thirteen serial positions around the target square. Scene memory was assessed in a forced choice recognition test at the end of the experiment. If increasing attention to a target leads to widespread increases in perceptual processing, then scenes that are presented at the same time as a target square should be better remembered than those presented with

[1]Although targets are typically construed as items that lead to an overt or covert response, we define targets as items that lead to a change in planned behavior, including a no-go cue (cf. Makovski et al., 2012). These items require the updating of goal states and could therefore also lead to greater perceptual processing (e.g., Donchin and Coles, 1988; Aston-Jones and Cohen, 2005; Bouret and Sara, 2005; Zacks et al., 2007).

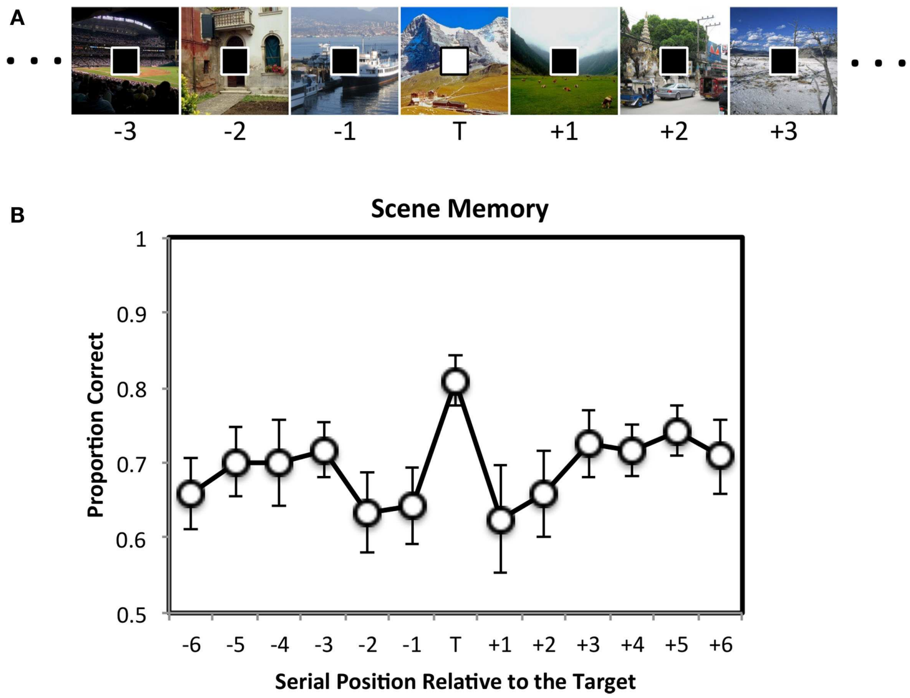

FIGURE 1 | The attentional boost effect. (A) Participants memorized scenes (500 ms duration, 0 ms ISI) for a later memory test. At the same time, they also pressed a key as quickly as possible whenever the square presented at fixation was white instead of black. Stimuli are not drawn to scale. **(B)** Later recognition memory for the scenes was enhanced if the scene was presented at the same time as a target square during encoding. Error bars = ±1 standard error of the mean. Adapted from Swallow and Jiang (2010).

a distractor square[2] (*enhancement hypothesis*). However, because perceptual and control processes are limited (Lavie, 2005), targets should also reduce the availability of attention for processing the scene. Encoding scenes into memory requires attention (Wolfe et al., 2007). Target detection should therefore interfere with memory for images that coincide with, and even closely follow a target (*interference hypothesis*). This, however, did not occur. Instead, memory for scenes that were presented at the same time as a target square was enhanced relative to those presented with a distractor square (**Figure 1B**). No consistent differences were observed in memory for scenes that appeared with a distractor in the other serial positions. These data suggest that perceptual processing increases when behaviorally relevant events occur, resulting in a global enhancement of multiple competing tasks.

Importantly, this pattern of data could not be attributed to the perceptual salience of the rare, white square (Swallow and Jiang, 2010). No memory advantage was observed for scenes that were presented at the same time as a white square when the squares were ignored. In addition, the effect was not due to a motor response, as it also occurred when participants were asked to covertly count the number of target squares (Swallow and Jiang, 2012). Although detecting the target square required more attention than rejecting a distractor square (Duncan, 1980; Raymond et al., 1992), increasing attention to the square task boosted performance in the second task – an *attentional boost effect* (Swallow and Jiang, 2010)[3].

The attentional boost effect is not limited to tasks that require participants to actively encode stimuli for a later memory test. In an experiment examining implicit memory (Spataro et al., 2013), participants read aloud words that were individually presented at a rate of 2 per second. Each time a word appeared a green or red circle appeared below it. In the divided attention condition, participants pressed a button when the circle was green. In the full attention condition, they ignored the circle. After completing the encoding task and a brief delay, participants performed a lexical decision task on exposed and unexposed words. Remarkably, words that coincided with targets produced nearly twice as much priming as words that coincided with distractors. Moreover, this advantage was absolute: priming was greater for words presented with targets than for words in the full attention condition. This pattern of data was replicated in a word fragment completion task. It did not, however, occur in a conceptual priming task, suggesting that target detection enhanced the perceptual encoding of concurrently presented words.

The effects of detecting a target on concurrent image processing can also be observed in short-term memory tasks. In their study,

[2]For consistency, we refer to items that could be targets, but are not, as distractors. Distractors in RSVP tasks may have different effects on task performance than distractors that appear at the same time as a target in flanker tasks. Although they do not divert spatial attention from the target, distractors in RSVP tasks mask the target and could trigger inhibitory processes (e.g., Olivers and Meeter, 2008).

[3]A memory enhancement for scenes presented with targets has been referred to elsewhere as *fast task-irrelevant perceptual learning* (Leclercq and Seitz, 2012a,b,c).

Lin et al. (2010) first familiarized participants with scenes. In a subsequent task, 16 familiar scenes were presented one at a time (133 ms duration, 367 ms ISI) on each trial. A letter was presented in the center of each scene, and participants reported the identity of the gray letter at the end of each trial. They were also shown a scene and asked to indicate whether it was presented during the trial. Thus, this and similar experiments (e.g., Leclercq and Seitz, 2012a) examined how detecting a target letter influenced memory for whether a familiar image was recently presented. Consistent with the effects of targets on long-term visual memory, target detection enhanced short-term source memory for scenes.

Target detection also enhances short-term memory for semantically impoverished stimuli (Makovski et al., 2011). Participants performed a change detection task on color arrays separated by a 1500 ms delay. A letter was presented at fixation and participants quickly pressed a button when the letter was a T. The letter could appear at the same time as the first color array, during the 1500 ms retention interval, or at the same time as the second color array. Participants were better able to detect a color change when a target letter was presented than when a distractor letter was presented. Importantly, this benefit occurred only when the target letter coincided with the first color array, suggesting that target detection facilitated the encoding of the color patches into memory, but not their retention or comparison to current perceptual input. Interestingly, these data might help account for an earlier report of enhanced change detection in scenes when targets are present (Beck et al., 2001). Although no statistical analyses were reported, performance on the change detection task was better when a target letter was present (41%) than when it was absent (51%). These data offer initial evidence that the selection of behaviorally relevant events enhances the encoding of information into short-term memory.

Other evidence that target detection produces broad encoding enhancements comes from a recent fMRI study (Swallow et al., 2012). Participants pressed a button as quickly as possible whenever a tone of a pre-defined pitch was presented over headphones. If increasing attention to an auditory target pulls perceptual resources away from visual regions of the brain (Shomstein and Yantis, 2004; Johnson and Zatorre, 2006), then activity in visual areas should decrease when an auditory target is presented. If, however, temporal selective attention leads to widespread perceptual enhancements, then activity in visual areas should increase more when an auditory target is presented, rather than a distractor. The data confirmed the latter prediction. Activity in early visual cortex increased when an auditory target was presented, rather than a distractor (**Figure 2**). These data indicate that the response of early visual areas to goal-relevant events (Jack et al., 2006) is mediated by attention. In addition, unlike spatial selective attention (e.g., Kastner et al., 1998; Silver et al., 2007), temporal selection of an auditory target produced effects that were not spatially localized and that decreased in magnitude from early to late visual areas. This effect was present when auditory tones were presented on their own and when they were presented at the same time as a face, scene, or scrambled image. Moreover, the same pattern occurred when visual targets were presented with visual scenes. Under these conditions, detecting a target in the central visual field led to enhanced activity in regions representing the visual periphery and in early auditory cortex. These data rule out the possibility that the increase in early visual cortical activity in response to target tones reflects purely multi-modal processing in a region that is traditionally considered unisensory (Brosch et al., 2005; Baier et al., 2006; Ghazanfar and Schroeder, 2006; Driver and Noesselt, 2008; Kayser et al., 2008). Rather, temporal selection of a target, but not distractor rejection, boosts activity in perceptual regions of the brain that are not involved in its processing (*target-mediated boost*).

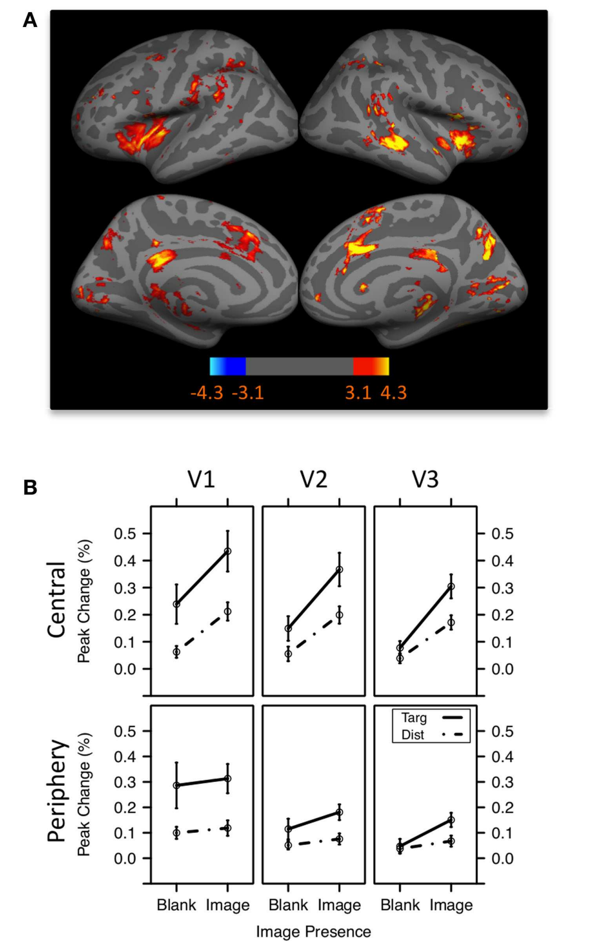

FIGURE 2 | The target-mediated boost. **(A)** Target tones were associated with increased activity in a network of brain regions previously associated with attentional selection. Color bar values indicate z statistics for the target-distractor contrast. **(B)** Peak percent change in activity in retinotopically defined early visual areas V1, V2, and V3 representing the central and peripheral visual fields following tones. V1 increased more in activity following the presentation of a target tone than a distractor tone (indicated by the difference between the solid and dashed lines). The effect was present in both central and periphery regions, but diminished in magnitude from V1 to V3. Error bars represent ±1 standard error of the mean. Adapted from Swallow et al. (2012).

The effects of target detection on perceptual processing are not limited to tasks involving visual stimuli, or to situations in which the background image and the target overlap in space. As just reviewed, the target-mediated boost is observed even in a purely auditory task (Swallow et al., 2012). Furthermore, both long-term and short-term memory for scenes is enhanced when they coincide with the presentation of an auditory target, such as a high-pitched tone presented in a stream of low-pitched tones (Lin et al., 2010; Swallow and Jiang, 2010). Spatial overlap is also unnecessary. Short-term memory for color patches presented several degrees from fixation is enhanced by the presence of a target letter during encoding (Makovski et al., 2011), and scenes presented in an unattended location also benefit from target detection (Leclercq and Seitz, 2012a). Combined, these data suggest that target detection produces enhancements that are not specific to the spatial location or modality of the target.

Finally, perceptual learning data further support the claim that target detection results in widespread perceptual enhancements (Watanabe et al., 2001; Seitz and Watanabe, 2003). For these studies, participants identified gray letters in a stream of black letters. Each letter was presented in the center of an irrelevant random dot motion display (RDM). Motion coherence in these displays was below threshold, so learning was unconscious. Importantly, one direction was always paired with the gray target letters. Following nearly 20,000 trials, perceptual learning was obtained only for the direction of motion paired with the target letter, but not for motion directions paired with a distractor letter. Detecting the target letter increased sensitivity to concurrently presented, task-irrelevant, and unattended, perceptual information (Seitz and Watanabe, 2003). Interestingly, *task-irrelevant perceptual learning* (TIPL) is strongest for motion features processed in primary visual cortex (V1) and located near the target (Watanabe et al., 2002; Nishina et al., 2007). TIPL is clear evidence that behaviorally relevant events can influence context processing. However, it is slow to develop and restricted entirely to information that slips past attentional filters. In fact, no learning occurs when participants are able to detect the dominant direction of motion in the RDM displays and presumably suppress it (Tsushima et al., 2008; see also Dewald et al., 2011). Although there are similarities between TIPL and the attentional boost effect, inconsistencies such as these require further investigation.

Together these data indicate that selectively attending to behaviorally relevant events can enhance the processing of, and memory for, concurrently presented information. These effects are immediate and long lasting, influencing activity in perceptual regions of the brain (Swallow et al., 2012), short-term memory for color arrays and scenes (Lin et al., 2010; Makovski et al., 2011), long-term memory for visual stimuli (Swallow and Jiang, 2010), implicit memory for words (Spataro et al., 2013), and perceptual sensitivity to orientations and directions of motion (Seitz and Watanabe, 2003; Seitz et al., 2009). The fact that many of these effects occur cross-modally suggests that detecting goal-relevant events such as a target has broad effects on perceptual processing.

The attentional boost effect can be distinguished from previous demonstrations of enhancements that occur across tasks. Previous observations that two tasks and stimuli can interact have been limited to situations in which the tasks and items are semantically congruent. For example, masked images (e.g., a dog) are more easily identified when they are presented at the same time as a semantically congruent sound (e.g., barking), rather than an incongruent sound (e.g., hammering; Chen and Spence, 2010; see also Griffin, 2004). Furthermore, holding a word or image in memory increases the likelihood that semantically congruent stimuli will be attended (Soto and Humphreys, 2007). In contrast to these findings, the attentional boost effect is unique in demonstrating that cross-task enhancements can occur for stimuli that are unrelated but concurrently presented. The targets and distractors are completely unrelated to the background images.

TEMPORAL SELECTION DRIVES THE ATTENTIONAL BOOST EFFECT

The experiments just reviewed point to a robust and broad processing advantage for information that coincides with targets. These data contradict the near ubiquitous finding that increasing attention to one task impairs performance on another (Kinchla, 1992). The availability of attentional resources appears to vary rapidly over time and is greater in some moments (when targets are detected) than in others. This fluctuation creates difficulties for limited-capacity theories such as the load theory. As a result, it is of critical importance to address whether alternative explanations can account for the attentional boost effect.

An immediate concern is that detecting a target may not have required more attention than did rejecting a distractor. Although target detection demands attention (Duncan, 1980; Chun and Potter, 1995), it is possible that the target square was too easily distinguished from the distractor squares and did not sufficiently tax perceptual resources. To address this concern, in one study we changed the simple color-detection task to a task that involved conjunction search (Swallow and Jiang, 2010). For this task, participants pressed a button for a target letter (e.g., a Red-X) that differed from distractor letters (e.g., Red-Y's and Blue-X's) in the combination of color and shape. Under these conditions, the target was perceptually similar to distractors, so perceptual load should have been high (Lavie and Tsal, 1994). In addition, distinguishing targets from distractors when they are defined by the conjunction of two features requires selective attention (Treisman and Gelade, 1980). The attentional boost effect was found under these conditions, indicating that it occurs even when targets are difficult to distinguish from distractors.

Another class of potential explanations for the attentional boost effect stem from the possibility that it reflects attentional phenomena that have already been well characterized in the literature. In particular, targets may have alerted participants and increased arousal, effectively increasing the amount of attention available to perform the two tasks (Posner and Boies, 1971). However, an inspection of **Figure 1B** makes it clear that there was no memory advantage for scenes that were presented immediately after the target, when the effects of alerting and arousal should have been greatest. Memory for scenes that followed a target was no better than memory for scenes that preceded it (Swallow and Jiang, 2010, 2011). Moreover, temporal selective attention produces a pattern of brain activity in early visual cortex that is distinct from the effects of alerting and arousal. Unlike alerting, detecting an auditory or visual target increases activity more strongly in primary visual cortex (Swallow et al., 2012), than in late visual areas (Anderson et al., 2003; Thiel et al., 2004; Fan et al., 2005).

Another possibility is that the target could have cued attention to the background scene. Attentional orienting in response to a cue has its largest effects 100–200 ms later (Nakayama and MacKeben, 1989; Egeth and Yantis, 1997). If the target acts as an attentional cue, then images that are presented during this brief time window should be better encoded into memory than those presented at the same time as a target. However, this is not the case. In one experiment (Swallow and Jiang, 2011) faces were presented for 100 ms and then masked for 400 ms (**Figure 3**). In different blocks of trials the target and distractor squares either onset at the same time as the face, or onset over the mask 100 ms before the face was presented. A memory advantage was observed only for faces that onset at the same time as the target. Moreover, another experiment found no evidence of enhanced memory for a face when it preceded a target (Swallow and Jiang, 2011), suggesting that the effects of target detection are temporally constrained.

Alternatively, it is possible that the effects of target detection on learning and memory are due to their distinctiveness. Items that are semantically or perceptually distinct from other items in a study list are better remembered than those that are not (Schmidt, 1991; Fabiani and Donchin, 1995; Hunt, 1995). However, recent data indicate that the attentional boost effect in short- and long-term memory is just as strong when target squares are as common as distractors (a 1:1 target to distractor ratio) and when they are relatively rare (a 1:6 ratio; Makovski et al., 2011; Swallow and Jiang, 2012). The target-mediated boost in fMRI is also observed when targets and distractors are equally frequent (Swallow et al., 2012). Moreover, poorer memory is observed for images that coincide with infrequent distractors rather than with distractors that are common (Swallow and Jiang, 2012). Distinctiveness is neither necessary nor sufficient for the attentional boost effect.

A final consideration is the nature of the attentional boost effect itself. Rather than an enhancement due to target detection, the attentional boost effect could reflect poorer memory for images presented with distractors. Several lines of evidence argue against this possibility. First, TIPL represents an increase in sensitivity for visual features that coincide with a target following training, and no change in sensitivity for those that coincide with distractors (Seitz and Watanabe, 2009). Second, in a study examining short-term memory for familiar scenes, scene memory was significantly above chance only when it was paired with a target, but not when the scene appeared on its own or with a distractor (Lin et al., 2010). Third, when task demands were held constant, long-term memory for faces that were presented at the same time as a distractor was similar to that for faces that were presented on their own (**Figure 3**; Swallow and Jiang, 2011). Finally, priming is enhanced for words presented with a target circle and unaffected for words presented with a distractor circle, relative to a condition in which the circles were task-irrelevant (Spataro et al., 2013). It therefore appears that the relative advantage for visual information that coincides with a target, rather than a distractor, reflects an enhancement due to target detection.

RECONCILING THE ATTENTIONAL BOOST WITH LOAD

The available data support the contention that, despite requiring attention, detecting a target can boost the processing of concurrently presented information. This finding challenges the notion that all perceptual resources are used obligatorily (Lavie and Tsal, 1994): If perceptual processing broadly increases at some

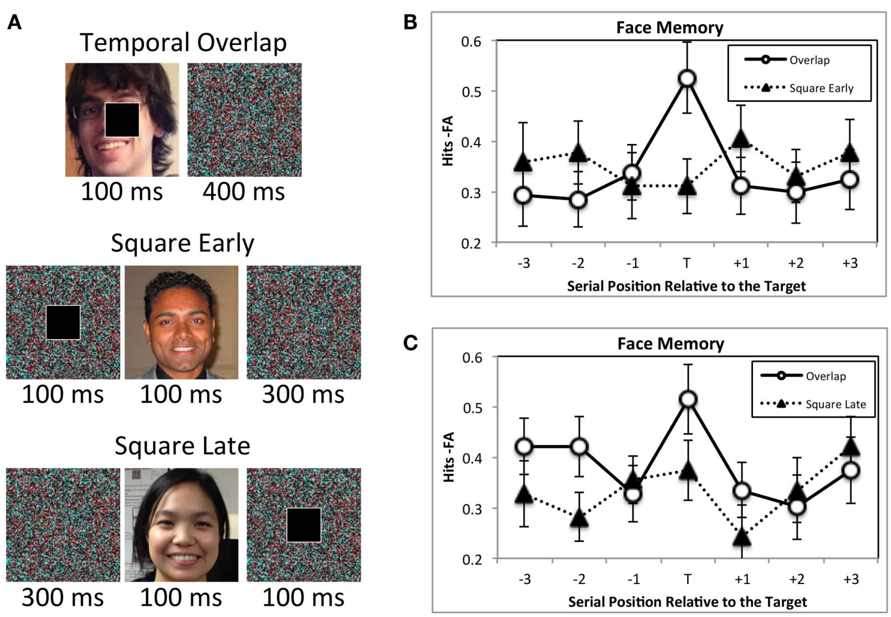

FIGURE 3 | The attentional boost effect occurs only for images that coincide with a target in time. (A) In two experiments participants were asked to memorize faces (100 ms duration, 400 ms mask; faces used in the experiment were famous), and to press a button when a white square, rather than a black square appeared (square duration = 100 ms). For one experiment the square and face onset at the same time in some blocks of trials (Temporal Overlap condition). In the other blocks of trials the square onset 100 ms before the face onset (Square Early condition). In the second experiment, temporal overlap blocks were interspersed with blocks in which the square onset 100 ms after the face (Square Late condition). **(B,C)** Target detection enhanced memory for faces only when the target and face overlapped in time. It did not facilitate memory for images that occurred 100 ms earlier **(B)** or 100 ms later **(A)**. Error bars represent ±1 standard error of the mean. Adapted from Swallow and Jiang (2011).

moments in time (e.g., when targets are detected), then it may not have been fully used at other moments in time. The attentional boost effect also represents a significant challenge to the long held view that performance in one task will suffer when another task or item requires more attention. If temporal selective attention of one target impairs the ability to detect a second target that is presented at the same time (Duncan, 1980), or soon after (Raymond et al., 1992), then how does it also enhance the encoding of concurrently presented perceptual information?

This section focuses on accounting for the potential effects of target detection on stimulus encoding. We propose that the encoding enhancement that is captured in the attentional boost effect and related phenomena represents a previously unrecognized feature of temporal selective attention that operates alongside dual-task interference.

Although many questions about the attentional boost effect remain, the available data provide a basis for proposing an extension to what is currently understood about temporal attention and selection. As in most models of attentional selection (e.g., Lavie and Tsal, 1994; Desimone and Duncan, 1995), the *dual-task interaction model* (**Figure 4**) proposes that task goals, maintained by a cognitive control mechanism like the central executive (Baddeley, 2003), prioritize the perceptual processing of goal-relevant stimuli. Goal-based attentional prioritization occurs early in perception, ensuring that relevant stimuli are perceptually processed. It also occurs post-perceptually, ensuring that those stimuli are maintained in memory if necessary and lead to task-appropriate responses. The dual-task interaction model is entirely consistent with load theory's claims that selection occurs at multiple stages, and that cognitive control plays a critical role in ensuring that relevant information is used to guide task performance (Lavie, 2005).

The dual-task interaction model extends load theory and other theories of dual-task performance with two components. The first is a broad attentional enhancement that is triggered by the appearance of a target in a stream of distractors. This enhancement roughly corresponds to temporal selective attention mechanisms described by others (e.g., Bowman and Wyble, 2007; Olivers and Meeter, 2008) and is closest conceptually to a model of the attentional blink that is based on the locus coeruleus–norepinephrine (LC-NE) system (Nieuwenhuis et al., 2005). However, the dual-task interaction model emphasizes the broad and spatially unconstrained perceptual enhancements that result from temporal selection. The second component is the coupling of task processes when stimuli are rhythmically presented. Although we propose that detecting a target always triggers an attentional

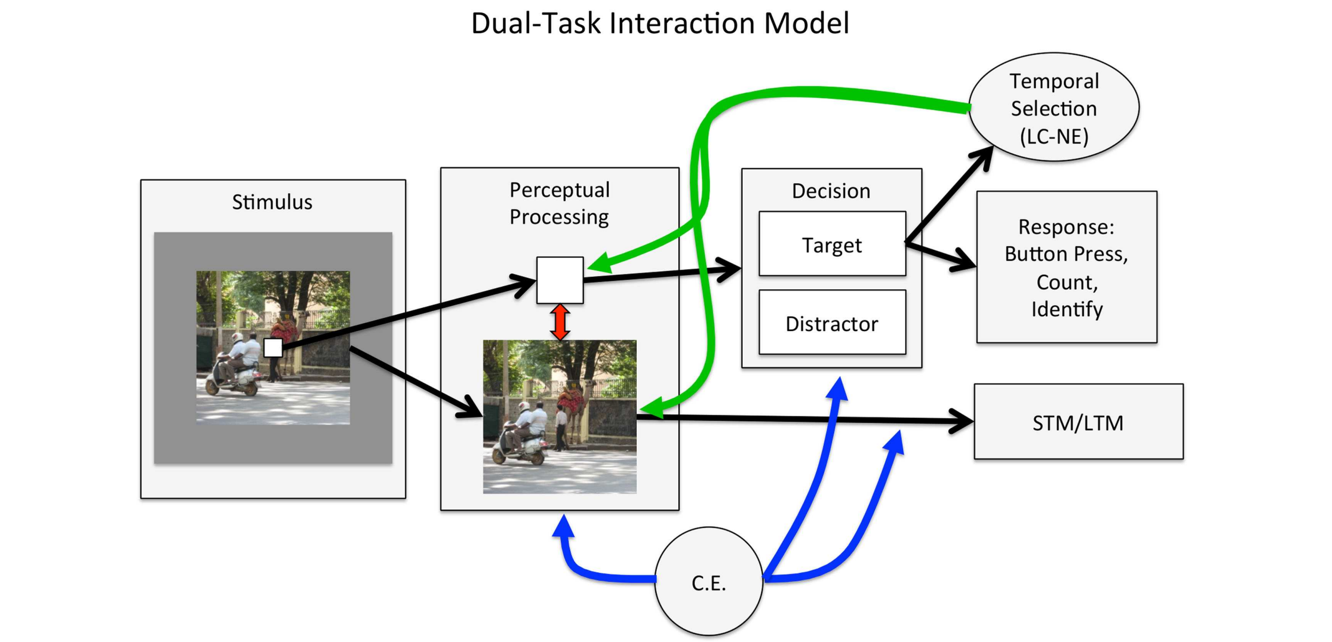

FIGURE 4 | The dual-task interaction model. On each trial, sensory information from the two task-relevant stimuli is selected to undergo perceptual processing (early selection), as directed by the central executive (CE). Within perceptual processing areas, the two stimuli compete for representation, producing dual-task interference. Dual-task interference also arises from the need to maintain multiple goals simultaneously: intentionally encoding the scene into memory, and generating an appropriate response to the square. Perceptual evidence that the square is a target or distractor is accumulated, and the square is categorized once a threshold has been reached. The item may then be selected to guide behavior and be maintained in memory if necessary (late selection). The categorization of the square as an item that requires a response (e.g., counting, holding on to the identity of the item in memory, or generating, or withholding, a planned motor response) triggers temporal selective attention. We propose that temporal selective attention, potentially instantiated by a transient increase in the release of norepinephrine from the locus coeruleus (LC-NE; Nieuwenhuis et al., 2005), is temporally, but not modality or spatially selective. It therefore enhances the processing of all perceptual information that is present when a target occurs. In addition, the detection of a target could reset neuronal activity across regions (Bouret and Sara, 2005; Lakatos et al., 2009). When stimuli are regularly presented, the consequent entrainment of neural activity to those stimuli could increase the efficiency of task processing.

enhancement, this effect may be more easily observed when the stimuli are rhythmically presented. Rhythmic stimulus presentation promotes efficient processing (Jones et al., 2002; Schroeder and Lakatos, 2009; Mathewson et al., 2010) and the temporal coupling of task processes.

TEMPORAL SELECTION BROADLY ENHANCES PERCEPTUAL PROCESSING

Within the dual-task interaction model, the decision that an item is a target leads to response selection and production, which are determined by the current goal set. It also leads to temporal selection, which enhances perceptual processing (**Figure 4**). To account for the finding that detecting a target results in the enhanced processing of the target and its context, the dual-task interaction model proposes that temporal selection is selective for time, but not for space or modality.

The target-mediated boost, makes it clear that temporal selective attention is not simply the brief application of spatial selective mechanisms (Swallow et al., 2012) (although the effects of both types of selection are likely to overlap and could interact; Coull and Nobre, 1998; Nishina et al., 2007; Leclercq and Seitz, 2012a). Indeed, the challenges facing temporal selection are distinct from those facing spatial selection. Rather than resolving competition in neural receptive fields (Desimone and Duncan, 1995), temporal selection must ensure that sufficient information is acquired about relevant items and their context before their processing is disrupted by new input. One way temporal selection may ensure that information about such items is available for task performance is to prioritize it for maintenance in short-term memory (e.g., Chun and Potter, 1995). However, perceptual processing takes time (Schyns and Oliva, 1994; Ploran et al., 2007) and encoding can be easily disrupted by new input (Breitmeyer and Ganz, 1976; Potter et al., 2004). Temporal selection therefore may also enhance perceptual processing to ensure that information about the relevant item and its context is encoded into memory. Without such an enhancement, perceptual information about behaviorally relevant items and their context could be lost.

The notion that temporal selection ensures that goal-relevant information is available to influence task performance may be best captured by theories that account for the attentional blink. Although they differ in their particulars, most theories of the attentional blink suggest that it reflects the protection of high-level representations of the target from interference (Dux and Marois, 2009). For example, in the Boost and Bounce Theory of temporal attention (Olivers and Meeter, 2008), the recognition of a target triggers an excitatory feedback response to perceptual areas, beginning with those that represent item identity. This response enhances, or boosts, the likelihood that a goal-relevant item will be maintained in working memory and, consequently, influence behavior. To avoid enhancing items that could interfere with task performance, the recognition of a distractor item results in inhibitory feedback to these same areas, reducing the likelihood that subsequent items will reach awareness. Similarly, the simultaneous type, serial token model (ST^2) proposed by Bowman and Wyble (2007) claims that the classification of an item as a target triggers an attentional "blaster." This blaster allows the features of the target item to be bound into an episodic and individuated representation that is actively maintained in memory until it is needed. In the ST^2 model, the enhancement is automatically followed by inhibition. In both of these models, the mechanism that produces the attentional blink most closely corresponds to late selection, as its primary function is to determine which stimuli reach awareness and working memory (Vogel et al., 1998), rather than to prevent the perceptual processing of task-irrelevant information.

Like most theories of temporal attention, these two theories focus on explaining how temporal attention protects a target item from interference at the same time that it suppresses the processing of items that soon follow it (Dux and Marois, 2009). Like load theory (Lavie and Tsal, 1994; Lavie et al., 2004) however, their focus is almost exclusively on how a single relevant item is prioritized. In contrast, the dual-task interaction model proposes that temporal selection also enhances perceptual processing in regions that are not involved in representing the target. Although it is not an explicit component of most theories of temporal selection, the LC-NE model (Nieuwenhuis et al., 2005) does suggest that the effects of temporal attention may in fact be widespread. The LC-NE account of the attentional blink proposes that it reflects the dynamics of the LC-NE response to targets. In monkeys, a behavioral response to targets is reliably preceded by a phasic increase in the release of norepinephrine from the LC (Aston-Jones et al., 1994). NE increases the responsivity of target neurons to their input (Servan-Schreiber et al., 1990; Aston-Jones and Cohen, 2005). As a result, it could provide the neurophysiological basis for temporal selection as well as the attentional blink (Aston-Jones and Cohen, 2005; Nieuwenhuis et al., 2005). Of importance to the dual-task interaction model, the LC projects widely throughout neocortex. The effects of the phasic LC-NE response to targets therefore are likely to be widespread, spanning different sensory modalities and representing different spatial locations (Aston-Jones and Cohen, 2005).

The neurophysiological mechanisms that underlie the attentional boost effect and related phenomena are unknown. However, the broad perceptual enhancements that result from target detection (Seitz and Watanabe, 2009; Lin et al., 2010; Swallow and Jiang, 2010, 2011; Makovski et al., 2012; Swallow et al., 2012; Spataro et al., 2013) are a plausible consequence of phasic LC-NE signaling.

One potential effect of temporal selective attention on neural processing could be to reset the phase of neural oscillations in a diverse network of cortical areas (Schroeder and Lakatos, 2009). This, combined with work suggesting that the phasic LC-NE response to goal-relevant events can reset neuronal activity (Bouret and Sara, 2005) reinforces the proposal that the effects of targets on neural activity are widespread. They may also provide an explanation for one of the more surprising aspects of the target-mediated boost (Swallow et al., 2012): Detecting an auditory tone increases activity in early visual areas, even when no visual stimuli were presented. It is possible that these data reflect the resetting of neuronal activity in these areas, modulating their sensitivity to new input (Lakatos et al., 2009). The next section discusses the consequences of phase resets in greater detail.

As with the phasic LC-NE response to targets (Aston-Jones and Cohen, 2005), we propose that the perceptual enhancements resulting from temporal selection occur whenever a target is detected. However, the ability to detect these enhancements is likely to be a function of many different factors. One factor is the presence of interference effects later in processing. Performance of even the simplest tasks involves multiple mechanisms, some that are parallel (e.g., perception) and some that are serial (e.g., response selection; Pashler, 1994). Although two stimulus streams may be perceptually processed in parallel, their encoding into working memory, and the generation of appropriate responses are likely to be limited by serial mechanisms (Pashler, 1994). Therefore, enhancements in perceptual processing may not translate into better performance when the consolidation or maintenance of perceptual information in long-term and short-term memory is disrupted. Indeed, increasing the difficulty of response selection by asking participants to make different, arbitrary responses to different targets eliminates (but does not reverse) the memory advantage for scenes presented at the same time as targets (Swallow and Jiang, 2010). Load theory (Lavie et al., 2004) also suggests that increasing cognitive load might interfere with the ability to observe the broad effects of temporal selection. Reducing the availability of cognitive resources to maintain or consolidate perceptual information into memory should reduce the utility of perceptual processing enhancements produced by temporal selection.

RHYTHMIC STIMULI PROMOTE THE COUPLING OF TASK PROCESSES

A second component of the dual-task interaction model is the proposal that the temporal structure of the stimulus streams may play a critical role in how much temporal selection for one task influences performance in another. Attentional boost effect experiments that irregularly presented task stimuli tended to show a weaker memory advantage for information that coincided with targets than experiments with regularly presented stimuli (e.g., 3–5% effects in Makovski et al., 2011 and Swallow et al., 2012 vs. 10–20% effects in Swallow and Jiang, 2010, 2011, 2012). This difference across studies could be explained by recent research that examines how rhythmic stimuli influence one's attentional state. Visual neural activity can entrain both to rhythmically presented stimuli and to activity in other sensory areas, enhancing the effects of temporal selection and integrating information across modalities (Large and Jones, 1999; Jones et al., 2002; Lakatos et al., 2007, 2008; Schroeder and Lakatos, 2009; Busch and VanRullen, 2010; Mathewson et al., 2010).

Neuronal oscillations correlate with how easily input can drive the activity of neural populations. In one influential study, Lakatos et al. (2008) trained monkeys to attend to either visual or auditory stimuli that were alternately presented in a continuous stream. Occasionally an oddball stimulus was presented, signaling the monkey to make a motor response. Two findings that are particularly relevant to the attentional boost effect were reported. First, activity in supragranular layers of visual cortex entrained to attended stimuli, regardless of whether those stimuli were presented in the auditory or visual modality. This entrainment could reflect the phase resetting of activity in visual cortex in response to an attended event (Lakatos et al., 2007). The second relevant finding was that the speed with which the monkeys responded to an oddball stimulus was influenced by when it occurred relative to the phase of low frequency (delta) neuronal oscillations. Faster responses were generated to stimuli presented when the neurons were most excitable (Lakatos et al., 2008; Schroeder and Lakatos, 2009).

Oscillatory activity in EEG recordings also appear to influence attention and perception in humans (Mathewson et al., 2009, 2010; Busch and VanRullen, 2010). Visual stimuli are more easily detected when they are presented at the peak of an alpha wave in EEG recordings (Mathewson et al., 2009). Moreover, behavioral data further indicate that the entrainment of cortical activity across visual and auditory regions has widespread effects on attention. Attention to an item is enhanced when it occurs at a moment in time that is predicted by the rhythm of stimuli that precede it, regardless of whether they were in the same or different modalities (Klein and Jones, 1996; Jones et al., 2002; Miller et al., 2013). It therefore appears that attention to rhythmic stimuli can encourage synchronous activity across a network of cortical areas (including those involved in higher-order cognitive processes, Besle et al., 2011), which in turn makes them maximally sensitive to input at similar points in time.

This possibility is captured in the proposal that attention to perceptual information operates in two different modes (Schroeder and Lakatos, 2009). In the *rhythmic* mode perceptual regions of the brain are maximally sensitive to input at the moment in time that input is expected (see also Large and Jones, 1999; Baier et al., 2006). The rhythmic mode is therefore advantageous when stimuli are presented in simple regular sequences. However, it comes with the cost of introducing long periods of time in which perceptual regions are less responsive to their input; periods of high excitability are interspersed with periods of low excitability. If stimuli appear irregularly or in isolation, then adopting a rhythmic processing mode could be maladaptive. In these situations, attention may shift into what Schroeder and Lakatos (2009) refer to as the *continuous* mode of processing. This processing mode is less efficient, but is also better able to maintain neural excitability over long periods of time.

In the dual-task interaction model we propose that the regular presentation of stimuli for both tasks encourages the adoption of a rhythmic processing mode. This, in turn, allows for greater apparent interaction between areas and processes that are involved in performing the detection task and the encoding task. In this situation, the broad effects of temporal selective attention may more efficiently influence multiple tasks and stimuli when regions involved in performing them are optimally excitable at the same time. As a result, the effects of temporal selection should be more easily detected when stimuli are presented regularly, rather than irregularly. In the latter condition, the attentional boost effect may be small and more difficult to detect.

LOAD THEORY AND THE DUAL-TASK INTERACTION MODEL

As reviewed previously, load theory (Lavie, 2005) proposes that limits in perceptual and cognitive processing are accommodated by both early and late selection mechanisms. Early selection ensures that perceptual resources are directed to goal-relevant items. Late selection ensures that goal-relevant items reach awareness and influence behavior once they have been perceptually processed. To account for the late selection data, load theory asserts that all perceptual resources are used: attended items are processed, but any perceptual capacity that remains spills over to irrelevant items (Lavie and Tsal, 1994).

The dual-task interaction model does not contradict the claim that selection can happen both early and late in processing. It is also consistent with dual-task interference and limitations in post-perceptual processing more generally (Pashler, 1994). According to the dual-task interaction model, responding to a target should increase demands on control processes. However, a corresponding reduction in control resources devoted to the encoding task can be offset by enhancements to perceptual processing that result from temporal selection. Thus, the dual-task interaction model reconciles the attentional boost effect with several aspects of load theory and the broader dual-task interference literature (e.g., Kinchla, 1992; Pashler, 1994).

The dual-task interaction model's suggestion that perceptual processing varies as a function of temporal selection, however, is difficult to reconcile with load theory's claim that all perceptual resources are obligatorily used (Lavie and Tsal, 1994). Although alerting and arousal are thought to influence the amount of available perceptual resources (Lavie and Tsal, 1994), the attentional boost effect conforms to neither of these (Swallow and Jiang, 2012; Swallow et al., 2012). In fact, the attentional boost effect lasts no more than 100 ms and is constrained to information presented concurrently with, rather than after, a target (Swallow and Jiang, 2011). If all available perceptual resources are used all the time, then it is not clear how such short-term variability in perceptual processing would occur, even in dual-task situations.

These inconsistencies suggest several possibilities. One is that this aspect of load theory is wrong – perceptual resources can be held in a reserve that is tapped when goal-relevant items appear. However, one could argue that we are comparing apples to oranges. Perceptual load theory describes attentional selection in space. In addition, whereas dual-task interference is important for explaining the effects of cognitive load on spatial selection, the effects of perceptual load can be observed in single tasks (Lavie, 2005). In contrast, the attentional boost effect involves selection over time and is usually observed in dual-task situations. However, the effects of target detection on early visual cortical activity occur even in single task situations (Swallow et al., 2012). Although one could argue that load theory accurately describes spatial selection processes, adhering to load theory's claim that all perceptual resources are used requires asserting that perceptual capacity rapidly increases when task-relevant events occur. It is not clear how such a claim could be falsified.

Another possibility is that the dual-task interaction model is wrong, and that temporal selective attention of a target item does not broadly enhance perceptual processing. Enhanced memory for a scene that coincides with a target could reflect post-perceptual effects of temporal selection. However, the data strongly suggest that target detection influences perceptual processing, even if it also influences post-perceptual processing. Target detection increases activity in early perceptual areas that are uninvolved in target processing (Swallow et al., 2012), enhances perceptual, but not conceptual priming (Spataro et al., 2013), and facilitates perceptual learning (Seitz and Watanabe, 2003). Although additional research is needed to clarify which stages of processing temporal selective attention enhances, the evidence points to perception.

A final possibility is that broad enhancements in perceptual processing produce unrecognized costs. Most studies of the attentional boost effect use recognition tests that do not capture differences in memory for perceptual details. Image encoding takes place at multiple scales, with coarser, more conceptual information extracted more rapidly than fine-grained perceptual details (Schyns and Oliva, 1994). Although memory for scene orientation was examined in one study (Swallow and Jiang, 2010), the data were noisy and inconclusive. Future research will need to determine whether temporal selection broadly enhances the processing of fine, as well as coarse, perceptual information.

IMPLICATIONS AND OPEN QUESTIONS

In its current form, the dual-task interaction model represents an initial attempt to account for the facilitatory effects of target detection on a concurrent encoding task, despite the increased demands on attention. Like the attentional boost effect itself, this model raises questions about the nature of temporal selective attention, its spatial characteristics, and the roles that load, reinforcement learning, and different attentional states may play in the ability to perform multiple tasks at once.

The dual-task interaction model proposes that temporal selection is broad and not constrained to particular locations or modalities. Although this claim is consistent with the available data, there is only one published study that attempts to address the spatial distribution of the effect (Leclercq and Seitz, 2012a). Additional research investigating both the spatial distribution and time course of temporal selective attention is needed. Moreover, the degree to which these effects are modulated by spatial attention and the relevance of the background information is also unclear. Most studies that have shown an effect of target detection on memory, rather than on perceptual learning, have done so by asking participants to attend to the background images (e.g., Lin et al., 2010; Swallow and Jiang, 2010; Spataro et al., 2013). In one study that examined incidental memory for the background scenes, no advantage for the scenes presented with targets was observed (Swallow and Jiang, 2011). Another recent study found that making targets difficult to perceive may eliminate the memory advantage for concurrently presented scenes (Huang and Watanabe, 2012). Along these lines, it will be important for future research to better characterize how different types of load influence the attentional boost effect. In its current form, the dual-task interaction model suggests that perceptual load and cognitive load may have very different effects on the ability of temporal selection to enhance perceptual processing. A better understanding of how attention and task relevance influence the attentional boost effect will be critical for the development of the dual-task interaction model and its reconciliation with load theory.

The close correspondence between the attentional boost effect and TIPL raises the question of whether they reflect the same mechanism operating on different time scales (Leclercq and Seitz, 2012a). In this and other papers we have proposed that this mechanism is temporal selection. However, TIPL has been explained by appealing to reinforcement learning in the attention-gated reinforcement learning model (AGREL; Seitz and Watanabe, 2009; Roelfsema et al., 2010). According to this perspective, detecting a target is intrinsically rewarding, and therefore triggers the release of neuromodulators that reinforce neural activity in perceptual areas. As a result, the visual system slowly becomes more sensitive to perceptual features that are present when a target occurs. This is consistent with the finding that external rewards, such as the delivery of water, also produce similar perceptual learning effects (Seitz et al., 2009). The dual-task interaction model, in contrast, suggests that the effects that are captured in short- and long-term memory reflect temporal selection rather than reinforcement learning. Although similar, the dual-task interaction and AGREL models differ in what they propose is happening in perceptual areas. Whereas the dual-task interaction model emphasizes that a boost in activity occurs, AGREL emphasizes that the underlying neural structures (e.g., connection strengths) are being altered. This likely reflects a difference in the phenomenon that is the focus of investigation – memory for scenes or perceptual learning – and it is certainly possible that target detection results in both temporal selection and reinforcement learning. Attention and reward are closely related (Anderson et al., 2011), and their effects are difficult to disentangle (Maunsell, 2004). It will therefore be important to reconcile the AGREL and dual-task interaction models in the future.

Finally, additional research exploring the attentional boost effect in neuropsychological populations and in development could be invaluable for testing several claims of the dual-task interaction model. For example, examining whether the attentional boost effect is observed throughout the visual field in spatial neglect patients would provide a new test of how temporal selective attention and spatial selection interact (Robertson et al., 1998). Similarly, studying whether the attentional boost effect is present or impaired when the dopamine system is compromised, as in Parkinson's disease and schizophrenia (Schultz, 1998), could shed light on the role of reinforcement learning in the effect. In addition, a recent account of autism suggests that it could reflect dysregulation of the LC-NE system (Mehler and Purpura, 2009). It is therefore possible that examining the attentional boost effect in this population could provide valuable insight into the nature of the attentional boost effect, as well as into the role of the LC-NE system in autism. Finally, because the enhancements that result from target detection are observable in memory only when demands on control processes are relatively low, it may also be useful to look at how changes in the development of multi-tasking ability and control (Luciana et al., 2005) influence the effect of target detection in behavioral and in brain activity.

CONCLUSION

For decades research on attention and dual-task processing has been based on the notion that attention and cognition are limited in capacity, and research on these processes has consistently supported this claim. Recent data from the attentional boost effect, the target-mediated boost, and TIPL, however, suggest that there is more to attention than mitigating capacity limits in space. Rather, attending to a target can enhance the perceptual processing of concurrently presented information. Although not predicted by current theories of attention, these data can be accounted for by the proposal that temporal selective attention is broad in space, but selective in time. Additional research is needed to reconcile the dual-task interaction model with load theory's claim that all perceptual resources are obligatorily used.

REFERENCES

Anderson, A. K., Christoff, K., Panitz, D., Rosa, E. D., and Gabrieli, J. D. E. (2003). Neural correlates of the automatic processing of threat facial signals. *J. Neurosci.* 23, 5627–5633.

Anderson, B. A., Laurent, P. A., and Yantis, S. (2011). Value-driven attentional capture. *Proc. Natl. Acad. Sci. U.S.A.* 108, 10367–10371.

Aston-Jones, G., and Cohen, J. D. (2005). An integrative theory of locus coeruleus-norepinephrine function: adaptive gain and optimal performance. *Annu. Rev. Neurosci.* 28, 403–450.

Aston-Jones, G., Rajkowski, J., Kubiak, P., and Alexinsky, T. (1994). Locus coeruleus neurons in monkey are selectively activated by attended cues in a vigilance task. *J. Neurosci.* 14, 4467–4480.

Baddeley, A. (2003). Working memory: looking back and looking forward. *Nat. Rev. Neurosci.* 4, 829–839.

Bahrami, B., Lavie, N., and Rees, G. (2007). Attentional load modulates responses of human primary visual cortex to invisible stimuli. *Curr. Biol.* 17, 509–513.

Baier, B., Kleinschmidt, A., and Müller, N. G. (2006). Cross-modal processing in early visual and auditory cortices depends on expected statistical relationship of multisensory information. *J. Neurosci.* 26, 12260–12265.

Beck, D. M., Rees, G., Frith, C. D., and Lavie, N. (2001). Neural correlates of change detection and change blindness. *Nat. Neurosci.* 4, 645–650.

Besle, J., Schevon, C. A., Mehta, A. D., Lakatos, P., Goodman, R. R., McKhann, G. M., et al. (2011). Tuning of the human neocortex to the temporal dynamics of attended events. *J. Neurosci.* 31, 3176–3185.

Bouret, S., and Sara, S. J. (2005). Network reset: a simplified overarching theory of locus coeruleus noradrenaline function. *Trends Neurosci.* 28, 574–582.

Bowman, H., and Wyble, B. (2007). The simultaneous type, serial token model of temporal attention and working memory. *Psychol. Rev.* 114, 38–70.

Breitmeyer, B. G., and Ganz, L. (1976). Implications of sustained and transient channels for theories of visual pattern masking, saccadic suppression, and information processing. *Psychol. Rev.* 83, 1–36.

Broadbent, D. E. (1958). *The Selective Nature of Learning. In Perception and communication.* Elmsford, NY: Pergamon Press, 244–267.

Brosch, M., Selezneva, E., and Scheich, H. (2005). Nonauditory events of a behavioral procedure activate auditory cortex of highly trained monkeys. *J. Neurosci.* 25, 6797–6806.

Busch, N. A., and VanRullen, R. (2010). Spontaneous EEG oscillations reveal periodic sampling of visual attention. *Proc. Natl. Acad. Sci. U.S.A.* 107, 16048–16053.

Carmel, D., Fairnie, J., and Lavie, N. (2012). Weight and see: loading working memory improves incidental identification of irrelevant faces. *Front. Cogn.* 3:286. doi:10.3389/fpsyg.2012.00286

Chen, Y.-C., and Spence, C. (2010). When hearing the bark helps to identify the dog: Semantically-congruent sounds modulate the identification of masked pictures. *Cognition* 114, 389–404.

Chun, M. M., and Jiang, Y. (1998). Contextual cueing: implicit learning and memory of visual context guides spatial attention. *Cogn. Psychol.* 36, 28–71.

Chun, M. M., and Potter, M. C. (1995). A two-stage model for multiple target detection in rapid serial visual presentation. *J. Exp. Psychol. Hum. Percept. Perform.* 21, 109–127.

Coull, J. T., and Nobre, A. C. (1998). Where and when to pay attention: the neural systems for directing attention to spatial locations and to time intervals as revealed by both PET and fMRI. *J. Neurosci.* 18, 7426–7435.

de Fockert, J. W., Rees, G., Frith, C. D., and Lavie, N. (2001). The role of working memory in visual selective attention. *Science* 291, 1803–1806.

Desimone, R., and Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annu. Rev. Neurosci.* 18, 193–222.

Deutsch, J. A., and Deutsch, D. (1963). Attention: some theoretical considerations. *Psychol. Rev.* 70, 80–90.

Dewald, A. D., Sinnett, S., and Doumas, L. A. A. (2011). Conditions of directed attention inhibit recognition performance for explicitly presented target-aligned irrelevant stimuli. *Acta Psychol. (Amst.)* 138, 60–67.

Donchin, E., and Coles, M. G. H. (1988). Is the P300 component a manifestation of context updating? *Behav. Brain Sci.* 11, 357–374.

Driver, J. (2001). A selective review of selective attention research from the past century. *Br. J. Psychol.* 92, 53–78.

Driver, J., and Noesselt, T. (2008). Multisensory interplay reveals crossmodal influences on 'sensory-specific' brain regions, neural responses, and judgments. *Neuron* 57, 11–23.

Duncan, J. (1980). The locus of interference in the perception of simultaneous stimuli. *Psychol. Rev.* 87, 272–300.

Dux, P. E., and Marois, R. (2009). The attentional blink: a review of data and theory. *Atten. Percept. Psychophys.* 71, 1683–1700.

Egeth, H. E., and Yantis, S. (1997). Visual attention: control, representation, and time course. *Annu. Rev. Psychol.* 48, 269–297.

Fabiani, M., and Donchin, E. (1995). Encoding processes and memory organization: a model of the von Restorff Effect. *J. Exp. Psychol. Learn. Mem. Cogn.* 21, 224–240.

Fan, J., McCandliss, B. D., Fossella, J., Flombaum, J. I., and Posner, M. I. (2005). The activation of attentional networks. *Neuroimage* 26, 471–479.

Ghazanfar, A. A., and Schroeder, C. E. (2006). Is neocortex essentially multisensory? *Trends Cogn. Sci. (Regul. Ed.)* 10, 278–285.

Griffin, Z. M. (2004). The eyes are right when the mouth is wrong. *Psychol. Sci.* 15, 814–821.

Hanson, C., and Hirst, W. (1989). On the representation of events: a study of orientation, recall, and recognition. *J. Exp. Psychol. Gen.* 118, 136–147.

Huang, T.-R., and Watanabe, T. (2012). Task attention facilitates learning of task-irrelevant stimuli. *PLoS ONE* 7:e35946. doi:10.1371/journal.pone.0035946

Hunt, R. R. (1995). The subtlety of distinctiveness: What von Restorff really did. *Psychon. Bull. Rev.* 2, 105–112.

Jack, A. I., Shulman, G. L., Snyder, A. Z., McAvoy, M. P., and Corbetta, M. (2006). Separate modulations of human V1 associated with spatial attention and task structure. *Neuron* 51, 135–147.

James, W. (1890). *The Principles of Psychology*. New York: Dover Publications.

Johnson, J. A., and Zatorre, R. J. (2006). Neural substrates for dividing and focusing attention between simultaneous auditory and visual events. *Neuroimage* 31, 1673–1681.

Johnston, W. A., and Dark, V. J. (1986). Selective attention. *Annu. Rev. Psychol.* 37, 43–75.

Jones, M. R., Moynihan, H., MacKenzie, N., and Puente, J. (2002). Temporal aspects of stimulus-driven attending in dynamic arrays. *Psychol. Sci.* 13, 313–319.

Kahneman, D. (1973). *Attention and Effort*. Englewood Cliffs, NJ: Prentice-Hall.

Kastner, S., de Weerd, P., Desimone, R., and Ungerleider, L. G. (1998). Mechanisms of directed attention in the human extrastriate cortex as revealed by function MRI. *Science* 282, 108–111.

Kayser, C., Petkov, C. I., and Logothetis, N. K. (2008). Visual modulation of neurons in auditory cortex. *Cereb. Cortex* 18, 1560–1574.

Kinchla, R. A. (1992). Attention. *Annu. Rev. Psychol.* 43, 711–742.

Klein, J. M., and Jones, M. R. (1996). Effects of attentional set and rhythmic complexity on attending. *Percept. Psychophys.* 58, 34–46.

Lakatos, P., Chen, C.-M., O'Connell, M. N., Mills, A., and Schroeder, C. E. (2007). Neuronal oscillations and multisensory interaction in primary auditory cortex. *Neuron* 53, 279–292.

Lakatos, P., Karmos, G., Mehta, A. D., Ulbert, I., and Schroeder, C. E. (2008). Entrainment of neuronal oscillations as a mechanism of attentional selection. *Science* 320, 110–113.

Lakatos, P., O'Connell, M. N., Barczak, A., Mills, A., Javitt, D. C., and Schroeder, C. E. (2009). The leading sense: supramodal control of neurophysiological context by attention. *Neuron* 64, 419–430.

Large, E. W., and Jones, M. R. (1999). The dynamics of attending: How people track time-varying events. *Psychol. Rev.* 106, 119–159.

Lassiter, G. D., and Slaw, R. D. (1991). The unitization and memory of events. *J. Exp. Psychol. Gen.* 120, 80–82.

Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. *J. Exp. Psychol. Hum. Percept. Perform.* 21, 451–468.

Lavie, N. (2005). Distracted and confused? Selective attention under load. *Trends Cogn. Sci. (Regul. Ed.)* 9, 75–82.

Lavie, N., Hirst, A., de Fockert, J. W., and Viding, E. (2004). Load theory of selective attention and cognitive control. *J. Exp. Psychol. Gen.* 133, 339–354.

Lavie, N., and Torralbo, A. (2010). Dilution: a theoretical burden or just load? A reply to Tsal and benoni (2010). *J. Exp. Psychol. Hum. Percept. Perform.* 36, 1657–1664.

Lavie, N., and Tsal, Y. (1994). Perceptual load as a major determinant of the locus of selection in visual attention. *Percept. Psychophys.* 56, 183–197.

Leclercq, V., and Seitz, A. R. (2012a). The impact of orienting attention in fast task-irrelevant perceptual learning. *Atten. Percept. Psychophys.* 74, 648–660.

Leclercq, V., and Seitz, A. R. (2012b). Fast task-irrelevant perceptual learning is disrupted by sudden onset of central task elements. *Vision Res.* 61, 70–76.

Leclercq, V., and Seitz, A. R. (2012c). Enhancement from targets and suppression from cues in fast task-irrelevant perceptual learning. *Acta Psychol. (Amst.)* 141, 31–38.

Lin, J. Y., Pype, A. D., Murray, S. O., and Boynton, G. M. (2010). Enhanced memory for scenes presented at behaviorally relevant points in time. *PLoS Biol.* 8:e1000337. doi:10.1371/journal.pbio.1000337

Luciana, M., Conklin, H. M., Hooper, C. J., and Yarger, R. S. (2005). The development of nonverbal working memory and executive control processes in adolescents. *Child Dev.* 76, 697–712.

Makovski, T., Jiang, Y. V., and Swallow, K. M. (2012). How do observer's responses affect visual long-term memory? *J. Exp. Psychol. Learn. Mem. Cogn.* PMID: 23206170. [Epub ahead of print].

Makovski, T., Swallow, K. M., and Jiang, Y. V. (2011). Attending to unrelated targets boosts short-term memory for color arrays. *Neuropsychologia* 49, 1498–1505.

Mathewson, K. E., Fabiani, M., Gratton, G., Beck, D. M., and Lleras, A. (2010). Rescuing stimuli from invisibility: Inducing a momentary release from visual masking with pre-target entrainment. *Cognition* 115, 186–191.

Mathewson, K. E., Gratton, G., Fabiani, M., Beck, D. M., and Ro, T. (2009). To see or not to see: prestimulus α phase predicts visual awareness. *J. Neurosci.* 29, 2725–2732.

Maunsell, J. H. R. (2004). Neuronal representations of cognitive state: reward or attention? *Trends Cogn. Sci. (Regul. Ed.)* 8, 261–265.

Mehler, M. F., and Purpura, D. P. (2009). Autism, fever, epigenetics and the locus coeruleus. *Brain Res. Rev.* 59, 388–392.

Miller, J. E., Carlson, L. A., and McAuley, J. D. (2013). When what you hear influences when you see listening to an auditory rhythm influences the temporal allocation of visual attention. *Psychol. Sci.* 24, 11–18.

Nakayama, K., and MacKeben, M. (1989). Sustained and transient components of focal visual attention. *Vision Res.* 29, 1631–1647.

Newtson, D., and Engquist, G. (1976). The perceptual organization of ongoing behavior. *J. Exp. Soc. Psychol.* 12, 436–450.

Nieuwenhuis, S., Gilzenrat, M. S., Holmes, B. D., and Cohen, J. D. (2005). The role of the locus coeruleus in mediating the attentional blink: a neurocomputational theory. *J. Exp. Psychol. Gen.* 134, 291–307.

Nishina, S., Seitz, A. R., Kawato, M., and Watanabe, T. (2007). Effect of spatial distance to the task stimulus on task-irrelevant perceptual learning of static Gabors. *J. Vis.* 7, 2.1–2.10.

Olivers, C. N. L., and Meeter, M. (2008). A boost and bounce theory of temporal attention. *Psychol. Rev.* 115, 836–863.

Pashler, H. (1994). Dual-task interference in simple tasks: data and theory. *Psychol. Bull.* 116, 220–244.

Pashler, H. E. (1998). *The Psychology of Attention*. Cambridge: MIT Press.

Ploran, E. J., Nelson, S. M., Velanova, K., Donaldson, D. I., Petersen, S. E., and Wheeler, M. E. (2007). Evidence accumulation and the moment of recognition: dissociating perceptual recognition processes using fMRI. *J. Neurosci.* 27, 11912–11924.

Posner, M. I., and Boies, S. J. (1971). Components of attention. *Psychol. Rev.* 78, 391–408.

Potter, M. C., Staub, A., and O'Connor, D. H. (2004). Pictorial and conceptual representation of glimpsed pictures. *J. Exp. Psychol. Hum. Percept. Perform.* 30, 478–489.

Raymond, J. E., Shapiro, K. L., and Arnell, K. M. (1992). Temporary suppression of visual processing in an RSVP task: an attentional blink? *J. Exp. Psychol. Hum. Percept. Perform.* 18, 849–860.

Robertson, I. H., Mattingley, J. B., Rorden, C., and Driver, J. (1998). Phasic alerting of neglect patients overcomes their spatial deficit in visual awareness. *Nature* 395, 169–172.

Roelfsema, P. R., van Ooyen, A., and Watanabe, T. (2010). Perceptual learning rules based on reinforcers and attention. *Trends Cogn. Sci. (Regul. Ed.)* 14, 64–71.

Schmidt, S. R. (1991). Can we have a distinctive theory of memory. *Mem. Cognit.* 19, 523–542.

Schroeder, C. E., and Lakatos, P. (2009). Low-frequency neuronal oscillations as instruments of sensory selection. *Trends Neurosci.* 32, 9–18.

Schultz, W. (1998). Predictive reward signal of dopamine neurons. *J. Neurophysiol.* 80, 1–27.

Schwan, S., and Garsoffky, B. (2004). The cognitive representation of filmic event summaries. *Appl. Cogn. Psychol.* 18, 37–55.

Schyns, P. G., and Oliva, A. (1994). From blobs to boundary edges: evidence for time- and spatial-scale-dependent scene recognition. *Psychol. Sci.* 5, 195–200.

Seitz, A. R., Kim, D., and Watanabe, T. (2009). Rewards evoke learning of unconsciously processed visual stimuli in adult humans. *Neuron* 61, 700–707.

Seitz, A. R., and Watanabe, T. (2003). Is subliminal learning really passive? *Nature* 422, 36.

Seitz, A. R., and Watanabe, T. (2009). The phenomenon of task-irrelevant perceptual learning. *Vision Res.* 49, 2604–2610.

Servan-Schreiber, D., Printz, H., and Cohen, J. D. (1990). A network model of catecholamine effects: gain, signal-to-noise ratio, and behavior. *Science* 249, 892–895.

Shomstein, S., and Yantis, S. (2004). Control of attention shifts between vision and audition in human cortex. *J. Neurosci.* 24, 10702–10706.

Silver, M. A., Ress, D., and Heeger, D. J. (2007). Neural correlates of sustained spatial attention in human early visual cortex. *J. Neurophysiol.* 97, 229–237.

Soto, D., and Humphreys, G. W. (2007). Automatic guidance of visual attention from verbal working memory. *J. Exp. Psychol. Hum. Percept. Perform.* 33, 730–737.

Spataro, P., Mulligan, N. W., and Rossi-Arnaud, C. (2013). Divided attention can enhance memory encoding: the attentional boost effect in implicit memory. *J. Exp. Psychol. Learn. Mem. Cogn.* PMID: 23356238. [Epub ahead of print].

Swallow, K. M., and Jiang, Y. V. (2010). The attentional boost effect: transient increases in attention to one task enhance performance in a second task. *Cognition* 115, 118–132.

Swallow, K. M., and Jiang, Y. V. (2011). The role of timing in the attentional boost effect. *Atten. Percept. Psychophys.* 73, 389–404.

Swallow, K. M., and Jiang, Y. V. (2012). Goal-relevant events need not be rare to boost memory for concurrent images. *Atten. Percept. Psychophys.* 74, 70–82.

Swallow, K. M., Makovski, T., and Jiang, Y. V. (2012). The selection of events in time enhances activity throughout early visual cortex. *J. Neurophysiol.* 108, 3239–3252.

Swallow, K. M., Zacks, J. M., and Abrams, R. A. (2009). Event boundaries in perception affect memory encoding and updating. *J. Exp. Psychol. Gen.* 138, 236–257.

Thiel, C. M., Zilles, K., and Fink, G. R. (2004). Cerebral correlates of alerting, orienting and reorienting of visuospatial attention: an event-related fMRI study. *Neuroimage* 21, 318–328.

Treisman, A. M. (1969). Strategies and models of selective attention. *Psychol. Rev.* 76, 282–299.

Treisman, A. M., and Gelade, G. (1980). A feature-integration theory of attention. *Cogn. Psychol.* 12, 97–136.

Tsal, Y., and Benoni, H. (2010). Diluting the burden of load: perceptual load effects are simply dilution effects. *J. Exp. Psychol. Hum. Percept. Perform.* 36, 1645–1656.

Tsushima, Y., Seitz, A. R., and Watanabe, T. (2008). Task-irrelevant learning occurs only when the irrelevant feature is weak. *Curr. Biol.* 18, R516–R517.

Vogel, E. K., Luck, S. J., and Shapiro, K. L. (1998). Electrophysiological evidence for a postperceptual locus of suppression during the attentional blink. *J. Exp. Psychol. Hum. Percept. Perform.* 24, 1656–1674.

Watanabe, T., Nanez, J. E., Koyama, S., Mukai, I., Liederman, J., and Sasaki, Y. (2002). Greater plasticity in lower-level than higher-level visual motion processing in a passive perceptual learning task. *Nat. Neurosci.* 5, 1003–1009.

Watanabe, T., Náñez, J. E., and Sasaki, Y. (2001). Perceptual learning without perception. *Nature* 413, 844–848.

Wilson, D. E., Muroi, M., and MacLeod, C. M. (2011). Dilution, not load, affects distractor processing. *J. Exp. Psychol. Hum. Percept. Perform.* 37, 319–335.

Wolfe, J. M., Horowitz, T. S., and Michod, K. O. (2007). Is visual attention required for robust picture memory? *Vision Res.* 47, 955–964.

Yi, D.-J., Woodman, G. F., Widders, D., Marois, R., and Chun, M. M. (2004). Neural fate of ignored stimuli: dissociable effects of perceptual and working memory load. *Nat. Neurosci.* 7, 992–996.

Zacks, J. M., Speer, N. K., Swallow, K. M., Braver, T. S., and Reynolds, J. R. (2007). Event perception: a mind/brain perspective. *Psychol. Bull.* 133, 273–293.

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Dissociating compatibility effects and distractor costs in the additional singleton paradigm

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The interpretation of identity compatibility effects associated with irrelevant items outside the nominal focus of attention has fueled much of the debate over early versus late selection and perceptual load theory. However, compatibility effects have also played a role in the debate over the extent to which the involuntary allocation of spatial attention (i.e., attentional capture) is completely stimulus-driven or whether it is contingent on top-down control settings. For example, in the context of the *additional singleton paradigm*, irrelevant color singletons have been found to produce not only an overall cost in search performance but also significant compatibility effects. This combination of search costs and compatibility effects has been taken as evidence that spatial attention is indeed allocated in a bottom-up fashion to the salient but irrelevant singletons. However, it is possible that compatibility effects in the additional singleton paradigm reflect parallel processing of identity associated with low perceptual load rather than an involuntary shift of spatial attention. In the present experiments, manipulations of load were incorporated into the traditional additional singleton paradigm. Under low-load conditions, both search costs and compatibility effects were obtained, replicating previous studies. Under high-load conditions, search costs were still present, but compatibility effects were eliminated. This dissociation suggests that the costs associated with irrelevant singletons may reflect filtering processes rather than the allocation of spatial attention.

Keywords: attentional capture, compatibility effects, top-down control, additional singleton paradigm, load theory

INTRODUCTION

Selective visual attention is a construct invoked to account for the fact that only a fraction of the information contained in the retinal image is processed to the point of influencing goal-oriented behavior. A controversial issue in research on visual attention concerns the point in the stream of visual information processing at which the system selects from the available information the subset that is passed on for further processing. Historically, this issue has been framed in terms of whether selection occurs before or after the processing of stimulus identity, with the former referred to as *early selection* and the latter as *late selection* (Broadbent, 1958; Deutsch and Deutsch, 1963; Treisman, 1969; Allport, 1977; Treisman and Gelade, 1980).

One approach to determining the locus of selection has been to evaluate the influence of the identity of stimuli that appear outside the nominal focus of attention. For example, in the classic *flankers task* pioneered by Eriksen and Eriksen (1974), observers respond to the identity of an attended letter at fixation, and the response compatibility of letters appearing outside the focus of attention is manipulated. The presence of *compatibility effects* in this paradigm has been taken as evidence that the processing of letter identity is not dependent on the prior allocation of attention (i.e., a late locus of selection). Miller (1987), for example, found that even when flanking letters never appeared as targets (and were therefore completely task-irrelevant), they still produced response compatibility effects when their appearance was correlated with particular targets. Others, however, have argued that flanker compatibility effects do, in fact, depend on the prior allocation of attentional resources (i.e., an early locus of selection). For example, Eriksen and Eriksen (1974) interpreted their original results as evidence for limitations in the ability to restrict the allocation of attention to the central letter. Yantis and Johnston (1990) found that although relatively simple, two-letter, arrays produced standard flanker effects, these effects were eliminated when displays increased to eight items. The authors suggested that flanker effects associated with simple display are the result of unfocused spatial attention that "spills over" onto irrelevant stimuli. In contrast, "cluttered" displays encourage more tightly focused attention, eliminating flanker effects. This proposal is consistent with a more recent theoretical treatment known as *load theory*, proposes that the apparent locus of selection depends on the interaction between the resources required to efficiently perform the task (i.e., load) and the resources available to do so (Yantis and Johnston, 1990; Lavie, 1995). Specifically, when the resource load of the central, focused-attention task is low, the available resources are not fully consumed, and the remaining resources are passively and automatically allocated to other items in the display, resulting in the processing of the identity of those items. When the resource load of the focused-attention task is high, there are no remaining resources available for the processing of irrelevant display information. In support of this notion, Lavie and her colleagues have shown that compatibility effects associated with irrelevant peripheral stimuli are indeed eliminated if the perceptual difficulty of the central task is increased (Lavie and Tsal, 1994; Lavie, 1995, 2000, 2005; Lavie and Cox, 1997; Lavie and Fox, 2000; but see Tsal and Benoni, 2010).

In addition to their role in the debate over the locus of attentional selection, compatibility effects have also played a role in a long standing debate over the degree to which irrelevant but salient stimuli involuntarily elicit shifts of spatial attention, a phenomenon referred to as *attentional capture.* On one side of the debate is the "pure-capture" perspective, according to which preattentive processing results in the purely bottom-up or stimulus-driven allocation of attention that is completely impervious to top-down attention set or behavioral goals (Theeuwes, 1992, 1994, 1995, 2010). On the other side of the debate is the "contingent capture" perspective, according to which attentional capture is dependent on whether the capturing stimulus carries properties that match the task-related top-down "set" of the observer (Folk et al., 1992, 1994, 2002; Folk and Remington, 1998; Wyble et al., 2013).

One of the strongest pieces of evidence in support of the pure-capture perspective comes from the "additional singleton" paradigm. In the typical task, participants search for a singleton target defined on one feature dimension and response time to discriminate the orientation of a line segment inside the target is measured as a function of whether an "additional singleton," defined on a different feature dimension, is also present in the display or not. For example, Theeuwes (1992) had subjects search for a singleton target defined as a green diamond among a variable number of green circles. The presence of an additional, irrelevant, color singleton distractor produced a significant cost in response time, and the magnitude of this effect was dependent on the salience of the distractor relative to the target. Given that participants knew the defining feature of the target (shape) with complete certainty, they should have been able to instantiate a selective top-down set for that feature. Thus, the fact that a salient distractor defined in an orthogonal feature dimension (color) produced a cost in performance is consistent with a model in which the allocation of spatial attention is driven entirely by bottom-up salience, independent of top-down set.

More importantly for the present purposes, Theeuwes (1995) used a compatibility manipulation to provide converging evidence for the capture of spatial attention by irrelevant, additional singletons. The same method as Theeuwes (1992) was employed, but the identity of the element inside the distractor singleton was systematically varied, such that half the time it was the same as the element in the target singleton, and half the time it was the identity of the other possible target element. The presence of the additional singleton produced both search costs as well as significant compatibility effects associated with the identity of the element inside that irrelevant singleton. The combination of these two effects was interpreted as strong evidence for shifts of spatial attention to the location of the distractor singleton that occur independent of top-down set.

However, several alternative accounts of the additional singleton effect have been proposed. For example, Bacon and Egeth (1994) have argued that although the costs associated with the presence of irrelevant singletons reflect shifts of spatial attention, those shifts reflect the adoption of a top-down "singleton search mode" in which the system is set for singletons in general. This is in contrast to "feature search mode" in which the system is set for particular feature values. In support of this claim, Bacon and Egeth (1994) showed that when participants are forced to look for a target defined by a specific feature (e.g., when the target shape appears among heterogeneous non-target shapes), the effect of irrelevant singletons is eliminated (see also Leber and Egeth, 2006; but see Theeuwes, 2004).

Another interpretation of the irrelevant singleton effect attributes distractor costs not to the capture of spatial attention, but to a form of non-spatial competition known as "filtering costs" (Kahneman et al., 1983; Folk and Remington, 1998). According to this account, when a distractor is present, preattentive segmentation of the display results in two objects that "pop-out" from the background elements (i.e., the target and the distractor, by virtue of their singleton status). In contrast, when no distractor is present, only one object (the target) pops out from the background. Thus, according to the filtering cost explanation, the increase in response time associated with the presence of an irrelevant distractor reflects a delay in the allocation of spatial attention as the system resolves the competition between the two objects with respect to which should be the recipient of an attentional shift.

However, if, as proposed by the filtering costs account, focal attention is not shifted to the location of the irrelevant singleton, then why does the identity of the distractor produce compatibility effects as in Theeuwes (1995)? One possibility is that the preattentive segmentation of the search displays into two objects (i.e., the target and distractor), results in a stimulus that not only requires a time-consuming filtering operation, but can be characterized as a "low-load" display. Consistent with this possibility, Lavie and Cox (1997) found that load is associated not with the total number of stimuli on the display but with the number of *salient* stimuli in the display. This finding suggests that the effective set-size (and therefore load) in the irrelevant singleton paradigm is determined by the number of singletons. Thus, according to load theory, even if focal attention is shifted directly to the target singleton after the filtering operation is complete, given that the effective set-size is two, there may be enough attentional capacity left over to allow the automatic, parallel processing of the target and distractor identities, resulting in both filtering costs and distractor compatibility effects on response time.

There is already evidence that manipulations of processing load can influence the degree to which irrelevant singletons produce compatibility effects, at least in serial visual search (as opposed to parallel feature search in the typical additional singleton paradigm). Theeuwes and Burger (1998) found that when serial search of a display is required to detect a target letter, the presence of a non-target color singleton distractor produced compatibility effects if there was uncertainty about the particular color assignment on a given trial. The authors concluded that the presence of compatibility effects shows that in the absence of top-down expectations regarding target and distractor colors, singleton distractors can capture attention even during serial visual search. However, when Gibson and Bryant (2008) added a load (set-size) manipulation to the same task, compatibility effects associated with the color singleton distractor were eliminated with increases in perceptual load. The authors concluded that rather than reflecting attentional capture, the compatibility effects reported by Theeuwes and Burger (1998) were due to the passive, parallel allocation of unconsumed resources to the processing of the singleton letter.

There is also evidence from other paradigms that when only two display elements are presented (i.e., under low-load conditions), items that are known to appear outside the focus of spatial attention can nonetheless produce significant compatibility effects. For example, Folk et al. (2009) used a spatial cuing task in which letters appeared inside boxes to the left and right of fixation. One of the letters (the target) was red and the other was white. In addition, on half the trials the identity of the non-target letter was compatible with the target, and on the other trials it was incompatible. The search display was preceded by a cue display in which sets of four, abruptly onset dots appeared around each of the boxes, with one set of dots (the cue) appearing in red and the other in white. The location of the cue was non-predictive of the subsequent target location. Significant cuing effects were obtained, confirming that attention had been captured to the location of the cue. A significant effect of compatibility was also obtained. Most importantly, compatibility effects were obtained even on valid cue trials. Thus, even when the attention was allocated to the location of the target (as independently confirmed by the cuing effect), the identity of the unattended non-target letter on the other side of fixation produced compatibility effects. The authors concluded that even when spatial attention is focused at one location, parallel processing of the identity of irrelevant information can occur under low-load conditions.

In summary, there is evidence from serial search tasks and spatial cuing experiments that compatibility effects associated with unattended stimuli can emerge under low-load conditions and that these effects reflect parallel processing associated with excess processing capacity. These studies call into question whether the compatibility effects associated with distractors in the additional singleton paradigm necessarily reflect the allocation of spatial attention, or whether they are the result of parallel processing under low processing load.

The present experiments were designed to determine the nature of the distractor compatibility effects found in the additional singleton paradigm by introducing a processing load manipulation. If, as argued by Theeuwes and colleagues, compatibility effects in this paradigm provide converging evidence for the capture of spatial attention by the singleton distractor, then they should always co-vary with the costs associated with the presence of the distractor. That is, if a distractor produces a cost in search time, it should also produce a compatibility effect because distractor costs are assumed to reflect the allocation of spatial attention to the distractor location. If, however, compatibility effects reflect parallel processing of target and distractor identity associated with "low-load" displays, and these effects are functionally distinct from the costs produced by the presence of a distractor (e.g., filtering costs), then it should be possible to dissociate distractor costs from compatibility effects. Specifically, if the perceptual load is increased, then compatibility effects should be selectively reduced or eliminated, leaving the costs associated with the presence of the distractor intact.

Perceptual load is typically manipulated by varying display size. However, in the additional singleton paradigm, the target and distractor are both singletons, and therefore "pop-out" independent of display size. Indeed, as discussed above, this feature of the additional singleton paradigm is what renders the displays "low load," in that regardless of display size, the displays are perceptually segmented into one or two objects (depending on whether a distractor is present or not). Therefore, in the present experiments perceptual load was instead manipulated by varying whether responses were contingent on the presence of a particular conjunction of features across feature dimensions (i.e., color and shape; see Lavie, 1995). In order to accomplish this, we used a version of the additional singleton paradigm in which the target and distractor singletons were both defined within the same feature dimension (color), but different with respect to the particular feature value (target singletons were green and distractor singletons were red). In Experiment 1, we first show that the typical additional-singleton effects can be obtained using such within-dimension singletons. Experiment 2 added the critical perceptual load manipulation. Specifically, the shapes of the display elements were varied between circles and squares and in the critical "high-load" condition, responses to the green target were contingent on the green singleton also being a circle; responses were to be withheld from a green square. Lavie (1995) has previously shown that this type of perceptual load manipulation can eliminate compatibility effects associated with non-target distractors in a flankers task. It is also important to note that this means of manipulating perceptual load involves no changes to the physical properties of the display between low- and high-load conditions. Therefore, according to the pure-capture perspective, it should have no effect on the bottom-up salience of the distractor, and consequently no influence on whether the singleton distractor captures attention. To anticipate the results, although the presence of a distractor produced a search cost regardless of load condition, significant compatibility effects were only obtained in the low-load condition. Experiment 3 shows that the elimination of compatibility effects under high load is not simply the result of an overall increase in response times associated with high-load conditions.

EXPERIMENT 1

Given that the additional singleton paradigm has traditionally involved target and distractor singletons defined across different feature dimensions (e.g., shape target paired with a color distractor), the first experiment was conducted to be sure that the basic additional-singleton and compatibility effects can be found using within-dimension color singletons defined by different colors. Specifically, participants searched for a green circle among white circles and responded to the identity of the letter (R or L) inside the green circle. On half the trials an additional red circle distractor appeared and the compatibility of the letter inside distractor, relative to the letter inside the target, was varied across trials (see **Figure 1**,top row).

MATERIALS AND METHODS

Participants

Twenty undergraduates from Villanova University participated in partial fulfillment of a course requirement. Participants

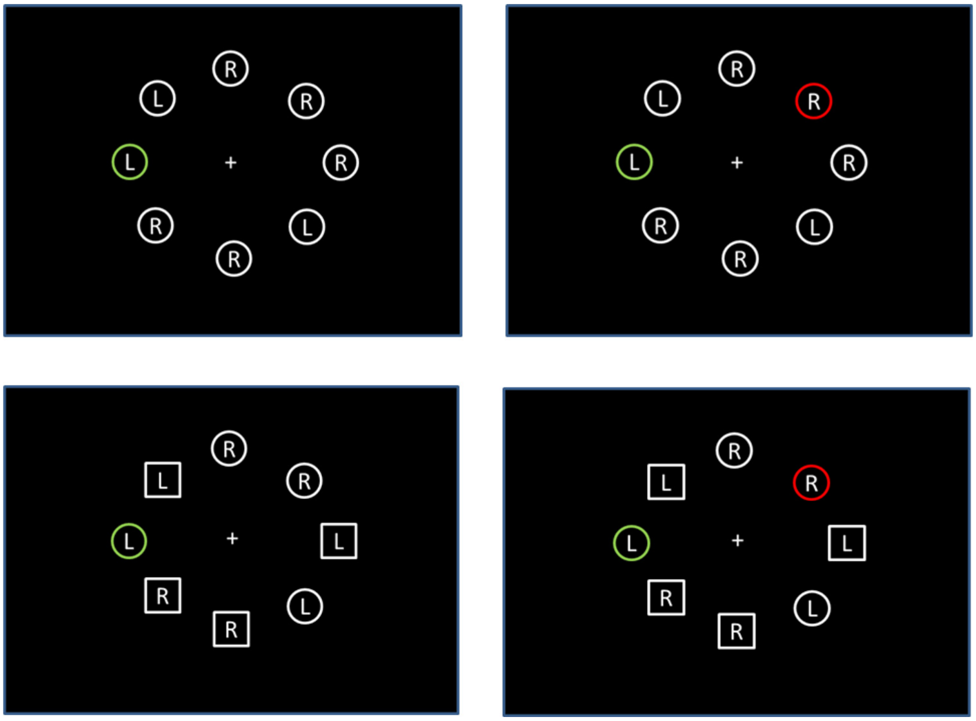

FIGURE 1 | Examples of displays from Experiments 1 (top row) and 2 (bottom row).

ranged in age from 18 to 20 years, and all were tested for normal or corrected-to-normal binocular near visual acuity (20/30 or better) and normal color vision using a Titmus II vision tester.

Apparatus

Stimuli were generated and responses collected by a Zenith 386 microcomputer equipped with a Sigma Design, Color 400 (680 × 400) graphics board. Stimuli were displayed on a Princeton Graphics Systems Ultrasync monitor. The monitor was placed in an enclosed viewing box at a distance of 50 cm.

Stimuli

Search displays consisted of either six or eight white (RGB: 255, 255, 255; CIE: $x = 0.35$, $y = 0.36$) circles (1.15° in diameter) equally spaced on the circumference of an imaginary circle (8.2° in diameter) centered on a white fixation cross (0.34° × 0.34°). Each circle contained either the letter "R" or the letter "L" (0.75° × 0.9°) displayed in white. On no-distractor trials one of the circles (i.e., the target) was green (RGB: 85, 255, 85; CIE: $x = 0.33$, $y = 0.55$). On distractor trials, in addition to the green target, one other circle (the distractor) was red (RGB: 255, 85, 85; CIE: $x = 0.56$, $y = 0.34$).

Design

An experimental session consisted of 5 blocks of 48 trials. Half the trials in each block contained six circles and half contained eight. In addition, for half the trials the green target circle contained the letter "R" and for half the letter "L." On distractor trials, the red circle contained the same letter as the target (compatible trials) on half the trials and the other letter on the other half of trials (incompatible trials). The identity of the letters in the other circles was determined randomly on each trial. The positions of the target and distractor were also determined randomly on each trial.

Procedure

The experimental session lasted approximately 1 h. Subjects were instructed to respond as quickly and accurately as possible, and to maintain fixation on the central fixation cross throughout each trial. Subjects were also fully informed with respect to the irrelevance of the distractors, and were encouraged to "ignore the distractor if possible."

The trial sequence began with the presentation of the fixation cross for 1 s. The cross then blinked off for 250 ms as a warning signal that the trial was beginning. The search display appeared 500 ms later and remained on the screen until the participant responded, at which point all stimuli were removed from the screen.

Subjects responded to target trials by pressing the "0" key on the numeric keypad of the computer keyboard with the forefinger of the their right hand if the letter inside the green target was an "R" and the left forefinger of the left hand if the letter inside the target was an "L." Response time was measured from the onset of the target display. Incorrect responses elicited a 500 ms, 1000-Hz computer tone, and were followed by a "buffer" trial with parameters drawn randomly from the set for that block. Response times for error and buffer trials were not included in the data analysis.

RESULTS

Response times as a function of display size and distractor condition are shown in **Figure 2** and error rates are reported in **Table 1**. The data were subjected to a 2 × 3 repeated measures ANOVA with display size (6, 8) and distractor condition (no distractor, compatible distractor, incompatible distractor) as factors. As is evident in the figure, the presence of a distractor produced a cost in response time that was confirmed by a significant main effect of distractor condition, $F(2,38) = 32.35$, MSE = 5296, $p < 0.0001$. Neither the main effect of display size nor the interaction were significant, $F < 1$ for both. To determine if the compatibility of the distractor influenced response time, a separate repeated measures ANOVA was conducted on just those trials containing a distractor, with compatibility and display size as factors. Only the main effect of compatibility was significant, $F(1,19) = 4.89$, MSE = 3315, $p < 0.05$.

Overall mean error rate was less than 1%. An ANOVA of the error data with display size and distractor as factors yielded only a main effect of distractor condition, $F(1,19) = 3.37$, MSE = 1.94, $p < 0.05$. As is evident in **Table 1**, this effect is associated with lower error rates in the compatible distractor condition.

DISCUSSION

The results of the first experiment show that when searching for a singleton of a specific color, the presence of additional singleton of a different color produces both a search cost as well as a compatibility effect. Having replicated the basic additional-singleton effects in the context of color singleton displays, we are now ready to institute variations in perceptual load by incorporating variations in the shape of the display elements and manipulating whether responses are contingent on a particular combination of color and shape (high load) or not (low load).

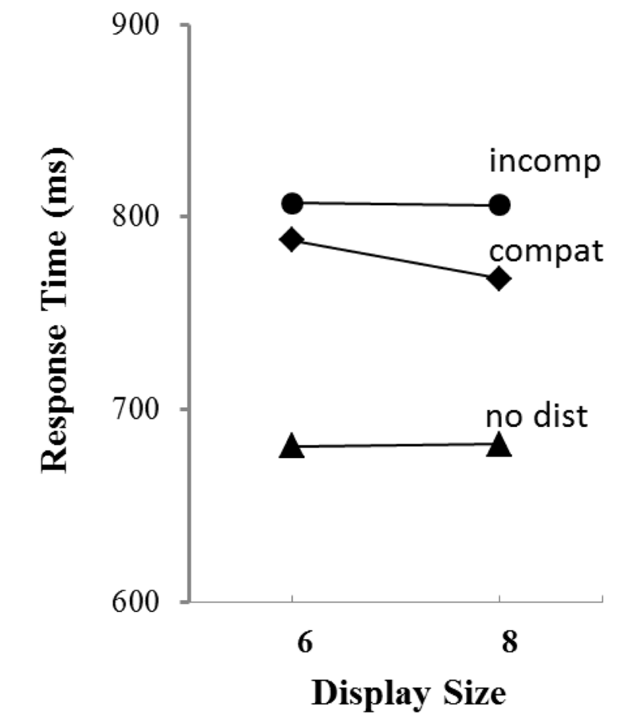

FIGURE 2 | Mean response time as a function of display size and distractor type in Experiment 1.

EXPERIMENT 2a AND 2b

Experiment 2 was similar to Experiment 1, with the exception that within each search display, half the elements were circles and half were squares. In Experiment 2a, the task was exactly the same as Experiment 1; participants responded to the identity of the letter inside the green item (regardless of whether it was a circle or square). In Experiment 2b, the displays were exactly the same, but participants were instructed to only respond if the green element was a circle; they were to withhold a response if the green element was a square (see **Figure 1**, bottom row).

MATERIALS AND METHODS

Participants

Twenty-four Villanova University undergraduates participated, 12 in Experiment 2a and 12 in Experiment 2b. All participated in partial fulfillment of a course requirement. Participants ranged in age from 18 to 20 years, and all were tested for normal or corrected-to-normal binocular near visual acuity (20/30 or better) and normal color vision using a Titmus II vision tester.

Apparatus

The apparatus was the same as Experiment 1.

Stimuli

Stimuli were the same as in Experiment 1, with the exception that half the elements in each display were circles and half were squares (1.5° × 1.5°). Green targets and red distractors could be either a circle or square.

Design

The design was similar to Experiment 1, except the number of blocks was increased to 8. In addition, within each block, the green target was a circle on two-thirds (32) of the trials and a square on one-third (16) of the trials. The red distractor was equally likely to be circle or a square.

Procedure

The procedure was identical to Experiment 1, with the exception that in Experiment 2b, subjects were instructed to only respond to the identity of the green target if it was a square. Otherwise, they were to withhold a response.

RESULTS

Experiment 2a

Response times as a function of display size and distractor condition are shown in left panel of **Figure 2** and error rates are reported in **Table 1**. The data were subjected to a 2 × 3 repeated measures ANOVA with display size (6, 8) and distractor condition (no distractor, compatible distractor, incompatible distractor) as factors. As in Experiment 1, the presence of a distractor produced a cost in response time that was confirmed by a significant main effect of distractor condition, $F(2,22) = 25.85$, MSE = 2580, $p < 0.0001$. The main effect of display size was not significant, $F(1,11) = 2.26$, MSE = 1008, $p > 0.10$, but the interaction was significant, $F(2,22) = 4.48$, MSE = 381,

Table 1 | Mean error rate as a function of distractor condition and display size for Experiments 1, 2a, 2b, and 3.

	Display size							
	Experiment 1		Experiment 2a		Experiment 2b		Experiment 3	
	6	8	6	8	6	8	6	8
Distractor condition								
No distractor	0.011	0.014	0.016	0.024	0.008	0.008	0.019	0.022
Compatible distractor	0.003	0.007	0.008	0.014	0.006	0.005	0.018	0.020
Incompatible distractor	0.011	0.012	0.018	0.019	0.004	0.003	0.025	0.021

$p < 0.05$. To determine if the compatibility of the distractor influenced response time, a separate repeated measures ANOVA was conducted on just those trials containing a distractor, with compatibility and display size as factors. Only the main effect of compatibility was significant, $F(1,11) = 22.48$, MSE = 17072, $p < 0.0001$.

Overall mean error rate was less than 2%. An ANOVA of the error data with display size and distractor as factors yielded no significant effects.

Experiment 2b

Response times as a function of display size and distractor condition are shown in the middle panel of **Figure 2** and error rates are reported in **Table 1**. The data were subjected to a 2 × 3 repeated measures ANOVA with display size (6, 8) and distractor condition (no distractor, compatible distractor, incompatible distractor) as factors. Once again, the presence of a distractor produced a cost in response time that was confirmed by a significant main effect of distractor condition, $F(2,22) = 219.77$, MSE = 1977, $p < 0.0001$. The main effect of display size was not significant, nor was the interaction, $F < 1$ for both. To determine if the compatibility of the distractor influenced response time, a separate repeated measures ANOVA was conducted on just those trials containing a distractor, with compatibility and display size as factors. Unlike Experiment 2a, the effect of compatibility was not significant, $F(1,11) = 0.08$, MSE = 1676, $p > 0.05$. The effect of display size and the interaction were also non-significant, $F < 1$ for both.

Overall mean error rate was less than 1%. An ANOVA of the error data with display size and distractor as factors yielded no significant effects.

Comparison of compatibility effects for Experiments 2a and 2b

To directly compare the impact of distractor compatibility under the different load conditions of Experiments 2a and 2b, the data from the conditions in which a distractor appeared were entered into a mixed factor ANOVA with Experiment (2a vs. 2b) as the between-subjects variable, and display size and compatibility as the within-subjects variables. The analysis yielded a significant main effect of compatibility, $F(1,22) = 12.22$, MSE = 1614, $p < 0.01$. Crucially, the interaction was also significant, $F(2,22) = 9.48$, MSE = 1614, $p < 0.01$, confirming that the manipulation of load across Experiments 2a and 2b significantly modulated the influence of distractor compatibility.

DISCUSSION

The results of Experiment 2 provide strong evidence that the compatibility effects associated with distractors in the additional singleton paradigm can be dissociated from the search costs produced by those same distractors. Specifically, although the displays were exactly the same in Experiments 2a and 2b, increasing the perceptual load by conditionalizing responses on a conjunction of color and shape in 2b completely eliminated the compatibility effect while leaving search costs intact. This pattern is inconsistent with the claim that the combination of search costs and compatibility effects constitute converging evidence for the capture of spatial attention by singleton distractors. If search costs reflect the allocation of spatial attention to the distractor, then the presence of such costs should always be associated with the presence of compatibility effects because attention has been allocated to the distractor letter. The fact that high perceptual load eliminated compatibility effects while leaving search costs intact is, however, consistent with the hypothesis that compatibility effects are produced by parallel processing of target and distractor in low-load displays, whereas search costs reflect delays associated with filtering processes (which should be unaffected by perceptual load).

It is important to point out, however, that the elimination of compatibility effects in the high-load condition was accompanied by an overall increase in response times, and are therefore confounded with overall task difficulty. It is possible that compatibility effects were generated even in the high-load conditions, but the overall increase in processing time allowed the effects to dissipate by the time response selection occurred. One way to rule out this possibility is to show that in low-load conditions, which we *know* produce compatibility effects (such as those in Experiment 1), the effects are still present when overall response times are increased. However, one must be careful that the manipulation used to increase overall response times does not itself affect perceptual load nor interfere with response selection. Therefore, Experiment 3 replicated the low perceptual load conditions of Experiment 1, but replaced the "R's" and "L's" with rotated "T's" and "L's." It was assumed that using rotated T's and L's would increase task difficulty by requiring the insertion of an additional mental process (mental rotation) that is associated with central processing resources and therefore does not increase perceptual load or interfere with response selection. Support for this assumption comes from Ruthruff et al. (1995) who using a psychological refractory period paradigm, showed that mental rotation requires central, rather than perceptual, processing resources. The general logic for addressing the task difficulty confound is similar to Lavie and DeFokert (2003) who showed that compatibility effects associated with low perceptual load conditions were still evident when general task difficulty was increased through sensory degradation. If compatibility effects associated with singleton distractors are simply be "hidden" by long overall response times, then assuming the rotation manipulation is successful, the compatibility effects found in Experiment 2 should not be evident in Experiment 3. If, however, compatibility effects do not dissipate with increases in overall response time, then the results should be similar to those found in Experiment 1.

EXPERIMENT 3

MATERIALS AND METHODS

Participants

Twenty Villanova University undergraduates participated in partial fulfillment of a course requirement. Participants ranged in age from 18 to 20 years, and all were tested for normal or corrected-to-normal binocular near visual acuity (20/30 or better) and normal color vision using a Titmus II vision tester.

Apparatus

The apparatus was the same as Experiment 1.

Stimuli

Stimuli were the same as in Experiment 1, with the exception that the "R's" and "L's" were replaced with "T's" and "L's" whose rotation with respect to vertical was chosen randomly from among 0°, 90°, 180°, and 270°.

Design and procedure

The design and procedure were identical to Experiment 1, with the exception that participants were instructed to press the "0" key on the numeric keypad of the computer keyboard with the forefinger of the their right hand if the letter inside the green target was an "T" and the left forefinger of the left hand if the letter inside the target was an "L."

RESULTS

Response times as a function of display size and distractor condition are shown in the right panel of **Figure 3** and error rates are reported in **Table 1**. The data were subjected to a 2 × 3 repeated measures ANOVA with display size (6, 8) and distractor condition (no distractor, compatible distractor, incompatible distractor) as factors. The only significant effect was a main effect of distractor condition, $F(2,38) = 48.68$, MSE = 1637, $p < 0.0001$. To determine if the compatibility of the distractor influenced response time, a separate repeated measures ANOVA was conducted on just those trials containing a distractor, with compatibility and display size as factors. Only the main effect of compatibility was significant, $F(1,19) = 20.21$, MSE = 716, $p < 0.0001$.

Overall mean error rate was less than 3%. An ANOVA of the error data with display size and distractor as factors yielded no significant effects.

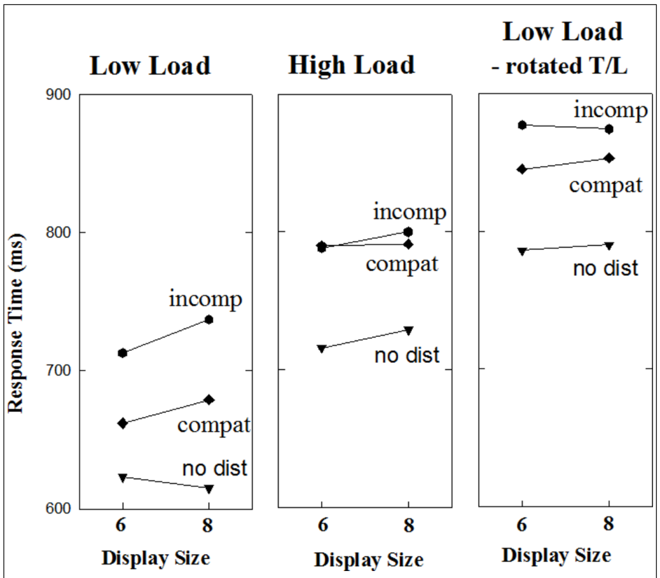

FIGURE 3 | Mean response time as a function of display size and distractor type in Experiments 2a (right panel), 2b (middle panel), and 3 (right panel).

DISCUSSION

As is evident in **Figure 3**, the present study was successful with respect to increasing overall response times. Most importantly, the compatibility effect remained intact even with overall response times similar to those found in Experiment 2b. Thus, it is reasonable to conclude that the lack of compatibility effects in Experiment 2b is not due to the dissipation of such effects with increased response times, but rather reflects the elimination of compatibility effects under high perceptual load. This strengthens the conclusion that compatibility effects can be dissociated from search costs in the additional singleton paradigm, and calls into question the claim that compatibility effects and search costs provide converging evidence for the capture of spatial attention by singleton distractors.

GENERAL DISCUSSION

Manipulations of the response compatibility of task-irrelevant stimuli have played an important role in the development of theories of selective attention. With respect to the present studies, such compatibility effects have been used to infer whether salient stimuli elicit involuntary shifts of spatial attention that are independent of top-down set. Specifically, the presence of both compatibility effects and search costs in the additional singleton paradigm have been interpreted as converging evidence for the purely bottom-up capture of attention by salient singletons (Theeuwes, 1996). However, evidence from other paradigms suggests that under low perceptual load conditions, the presence of compatibility effects can be dissociated from shifts of spatial attention, reflecting instead the parallel processing of the identity of task-irrelevant distractors due to availability of residual attentional capacity (Gibson and Bryant, 2008; Folk et al., 2009).

The present experiments were conducted to determine whether the compatibility effects found in the additional singleton paradigm reflect shifts of spatial attention, or parallel processing under low-load conditions. Experiment 1 replicated the basic additional singleton effect, showing that even when target and distractor singletons are defined by specific color values with the color dimension, the presence of a distractor singleton produces both search costs and compatibility effects. Experiments 2a and 2b introduced a load manipulation in which responses were (2b) or were not (2a) conditionalized on a particular combination of color and shape. Previous research using a flankers task has shown that this form of perceptual load manipulation modulates compatibility effects from irrelevant flankers. It was hypothesized that if search costs and compatibility effects provide convergent evidence for shifts of spatial attention, then they should both obtain regardless of perceptual load, because the bottom-up salience of the distractor does not change across load conditions, and any stimulus that captures attention should produce a compatibility effect. If, however, compatibility effects reflect parallel processing under low-load conditions rather than a shift of spatial attention, then they should decrease with increasing perceptual load while leaving search costs intact.

The results of Experiment 2 show that under low-load conditions, both search costs and compatibility effects were present, but under high-load conditions, only search costs were present. Experiment 3 confirmed that this effect is not simply due to the increase in overall response times, as search costs and compatibility effects were obtained for low-load displays in which overall response times were increased by increasing the time required to identify the target. Thus, the elimination of compatibility effects under high-load conditions in Experiment 2 suggests that rather than reflecting shifts of spatial attention, compatibility effects in this paradigm are due to parallel processing of the target and distractor when there is excess attentional capacity (i.e., under low-load conditions). Moreover, the clear dissociation between search costs and compatibility effects also calls into question whether search costs reflect shifts of spatial attention, since any stimulus to which spatial attention is directed should produce compatibility effects.

ALTERNATIVE INTERPRETATIONS

It is important, however, to consider other possible interpretations of the influence of load in the present experiments. For example, Belopolsky et al. (2007) have shown that whether a singleton distractor captures attention is dependent on the size of the "attentional window," which can be influenced by the difficulty of search. Specifically, increases in search difficulty require a smaller attentional window, resulting in a serial search strategy that eliminates capture. Thus, perhaps the high-load condition of Experiment 2 results in a smaller attentional window which prevents capture and therefore eliminates the compatibility effect. This possibility can be ruled out, however, because the presence of the distractor continued to produce search costs even in the high-load condition.

Another possibility is that our assumption about the asymmetric relationship between attention shifts and compatibility effects is wrong. We have assumed that if spatial attention is shifted to a stimulus it will always produce compatibility effects, whereas compatibility effects can obtain even in the absence of a shift of spatial attention (due, for example, to parallel processing under low-load conditions). However, logically, the absence of compatibility effects does not necessarily imply the absence of an attentional shift. For example, perhaps the singleton distractor does capture attention, but under high-load conditions attentional disengagement is so fast that the identity of the distractor is not processed (Theeuwes, 2010). Although logically possible, it is difficult to imagine how changing the response requirements for identical displays would result in changes in the speed of disengagement. In both conditions, the participants know that "red" is not the target color, and it is not clear why attention should be disengaged more rapidly when responses to the green target are contingent on its shape. Indeed, one might expect that when the task requires the consideration of shape as well as color, attention might tend to linger even longer on any given singleton.

Finally, one might also question whether our assumptions underlying the logic of Experiment 3 are valid. We assumed that the insertion of a mental rotation operation would increase task difficulty, and thereby lengthen overall response time, without affecting perceptual load or response selection. The fact that compatibility effects were still obtained under such an increase in difficulty was taken as evidence that the lack of compatibility effects in the critical high-load condition of Experiment 2b was not simply the result of the dissipation of the effect with longer response times. However, one might question whether the mental rotation required in Experiment 3 was as independent of response and perceptual processes as we assumed (Band and Miller, 1997; Heil et al., 1999; Pannebakker et al., 2011). For example, Pannebakker et al. (2011) found evidence that mental rotation can interfere with shifts of spatial attention. More importantly, Band and Miller (1997) found that mental rotation produced interference in response preparation. Thus, if the elimination of compatibility effects in Experiment 2 reflects response selection processes that, when given enough time, can counteract the activation of incompatible responses, then the mental rotation required in Experiment 3 might have interfered with those processes such that incompatible response activation could not be counteracted, even with longer overall response times. The present data cannot definitively rule out this alternative interpretation.

SPATIAL SHIFTS OR FILTERING COSTS?

The present results show that compatibility effects in the additional singleton paradigm can be influenced by perceptual load and can therefore be dissociated from search costs. As argued above, this dissociation implies that search costs produced by singleton distractors do not reflect the capture of spatial attention because if attention is allocated to the distractor, then the identity of the character at the distractor location should be processed, resulting in compatibility effects. We argue that the pattern of results in the present experiments is uniquely consistent with a filtering cost interpretation. According to this account, preattentive segregation of the typical additional singleton display results in the pop-out of the distractor and target. This has two dissociable consequences. First, when a singleton is present, it produces a competition with the target for the allocation of attention, which is ultimately resolved in the target's favor by virtue of a bias associated with the top-down set for the target color. We assume this competitive filtering process does not require resources, but does take time to complete. Thus, the presence of a distractor singleton produces a search cost that is not influenced by perceptual load. The second consequence is that the pop-out of the target and distractor singletons reduces the effective set-size of the search display to two, which can be characterized as a low-load display. Thus, even though focal attention is shifted only to the target, there are residual perceptual resources that they are allocated in parallel to the singleton distractor, resulting in the processing of its identity and the production of compatibility effects. When the perceptual resource requirements are increased in the high-load conditions, there are no longer residual resources available for distractor processing.

The conclusion that search costs in the additional singleton paradigm do not reflect shifts of spatial attention is consistent with several recent studies using event-related potential (ERP) measures (McDonald et al., 2013). For example, Jannati et al. (2013) measured ERP components associated with attention allocation (N2pc) and attentional suppression (P_D) while participants completed an additional singleton task in which the target singleton was defined by a fixed shape and the distractor singleton a fixed color. The presence of a distractor singleton produced a search cost relative to no distractor trials, replicating the standard additional-singleton effect. However, the ERP analysis showed that the salient distractor did not elicit an N2pc, but did elicit a P_D on fast-response trials. In addition, the target singleton did elicit an N2pc whose timing was unaffected by the presence of the salient distractor. The authors concluded that salient singletons in the additional singleton paradigm do not elicit shifts of attention, but do produce a time-consuming competition for attention that is resolved by suppressing the distractor location.

PERCEPTUAL LOAD OR DILUTION?

We have argued that the compatibility effects associated with distractor singletons in the additional singleton paradigm can be accounted for in terms of load theory (Lavie, 1995). However, Tsal and Benoni (2010) have recently argued that what appear to be perceptual load effects may actually reflect the "dilution" of perceptual encoding. According to this view, when "perceptual load" in a flankers task is manipulated by increasing display size (i.e., adding "neutral" letters), the elimination of flanker compatibility effects may result from the dilution of the flanker representations by the neutral letters rather than the unavailability of residual perceptual processing resources. This is because the processing of neutral letters activates feature detectors that would otherwise be devoted to the encoding of the irrelevant flanker, thereby diluting its effect. Consistent with this account, several studies have shown that flanker compatibility effects are eliminated under low-load but high-dilution conditions (Benoni and Tsal, 2010; Tsal and Benoni, 2010; Wilson et al., 2011). In the present experiments, however, the manipulation of processing load involved a change in the complexity of the perceptual operations required rather than any change in the properties of the displays. Thus, the degree of potential dilution (i.e., the degree to which feature detectors associated with letter identification are activated) was held constant across the low- and high-load conditions of Experiment 2. This suggests that the modulation of compatibility effects in the present experiments most likely reflects true load effects rather than dilution. It is important to point out, however, that regardless of the specific mechanism, the critical finding in the present studies is the dissociation between search costs and compatibility effects, which, as argued above, suggests that search costs do not reflect the capture of spatial attention.

CONCLUSION

The present experiments are the first to document a dissociation between search costs and compatibility effects in the additional singleton paradigm. Specifically, increasing perceptual load by conditionalizing responses on a conjunction of color and shape eliminated distractor compatibility effects while leaving distractor search costs intact. This pattern suggests that distractor compatibility effects in the additional singleton paradigm are the result of automatic, parallel identity processing in low-load displays. The results also highlight the fact that caution must be exercised in the interpretation of distractor compatibility effects in attentional capture paradigms, in that distractor compatibility effects can reflect processes other than shifts of spatial attention. This is not to say that compatibility effects can never be diagnostic of attention shifts, but that in order to conclusively tie compatibility effects to attentional capture, one must show that they covary with other, independent, measures of capture. For example, using a spatial cuing paradigm, Folk and Remington (2006) found compatibility effects associated with the presentation of spatial cues, but only when those cues also produced cuing effects indicative of an attentional shift to the cue.

Finally, the dissociation between search costs and compatibility effects in the present experiments suggests that the search costs in the additional singleton paradigm also do not reflect the capture of spatial attention. Specifically, if the costs were due to a shift of attention to the cue, then compatibility effects should have been present regardless of perceptual load. Therefore, the results undermine the claim that the additional singleton effect is strong evidence for the notion that attention allocation is driven solely by the bottom-salience of display elements. There is one final caveat, however. The present experiments explored the effects of perceptual load for singletons defined within the color dimension. Thus, additional research is needed to determine if the load effects found in the current experiments will generalize to additional singleton paradigms in which the target and distractor singletons are defined across dimensions (e.g., shape and color), or when the singleton distractor is defined by other stimulus properties such as abrupt onset (e.g., Schreij et al., 2008).

REFERENCES

Allport, A. (1977). "On knowing the meaning of words we are unable to report: the effects of visual masking," in *Attention and Performance*, Vol. 6, ed. D. S. Dornic (London: Academic Press), 505–534.

Bacon, W. F., and Egeth, H. E. (1994). Overriding stimulus-driven attentional capture. *Percept. Psychophys.* 55, 485–496. doi: 10.3758/BF03205306

Band, G. P. H., and Miller, J. (1997). Mental rotation interferes with response selection. *J. Exp. Psychol. Hum. Percept. Perform.* 23, 319–338. doi: 10.1037/0096-1523.23.2.319

Belopolsky, A. V., Zwann, L., and Theeuwes, J. (2007). The size of an attentional window modulates attentional capture by color singletons. *Psychon. Bull. Rev.* 14, 934–938. doi: 10.3758/BF03194124

Benoni, H., and Tsal, Y. (2010). Where have we gone wrong? Perceptual load does not affect selective attention. *Vis. Res.* 50, 1292–1298. doi: 10.1016/j.visres.2010.04.018

Broadbent, D. (1958). *Perception and Communication.* London: Pergamon Press. doi: 10.1037/10037-000

Deutsch, J. A., and Deutsch, D. (1963). Attention: some theoretical considerations. *Psychol. Rev.* 70, 80–90. doi: 10.1037/h0039515

Eriksen, B. A., and Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Percept. Psychophys.* 16, 143–149. doi: 10.3758/BF03203267

Folk, C. L., Leber, A. B., and Egeth, H. E. (2002). Made you blink! Contingent attentional capture produces a spatial blink. *Percept. Psychophys.* 64, 741–753. doi: 10.3758/BF03194741

Folk, C. L., and Remington, R. W. (1998). Selectivity in distraction by irrelevant featural singletons: evidence for two forms of attentional capture. *J. Exp. Psychol. Hum. Percept. Perform.* 24, 847–858. doi: 10.1037/0096-1523.24.3.847

Folk, C. L., Remington, R. W., and Johnston, J. C. (1992). Involuntary covert orienting is contingent on attentional control settings. *J. Exp. Psychol. Hum. Percept. Perform.* 18, 1030–1044. doi: 10.1037/0096-1523.18.4.1030

Folk, C. L., Remington, R. W., and Wright, J. H. (1994). The structure of attentional control: contingent attentional capture by apparent motion, abrupt onset, and color. *J. Exp. Psychol. Hum. Percept. Perform.* 20, 317–329. doi: 10.1037/0096-1523.20.2.317

Folk, C. L., and Remington, R. (2006). Top-down modulation of preattentive processing: testing the recovery account of contingent capture. *Vis. Cogn.* 14, 445–465. doi: 10.1080/13506280500193545

Folk, C. L., Remington, R. W., and Wu, S. C. (2009). Additivity of abrupt onset effects reflects non-spatial distraction, not the capture of spatial attention. *Atten. Percept. Psychophys.* 71, 308–313. doi: 10.3758/APP.71.2.308

Gibson, B. S., and Bryant, T. A. (2008). The identity intrusion effect: attentional capture or perceptual load. *Vis. Cogn.* 16, 182–199. doi: 10.1080/13506280701467987

Heil, M., Wahl, K., and Herbst, M. (1999). Mental rotation, memory scanning, and the central bottleneck. *Psychol. Res.* 62, 48–61. doi: 10.1007/s004260050039

Jannati, A., Gaspar, J. M., and McDonald, J. J. (2013). Tracking target and distractor processing in fixed-feature visual search: evidence from human electrophysiology. *J. Exp. Psychol. Hum. Percept. Perform.* doi: 10.1037/a0032251 [Epub ahead of print].

Kahneman, D., Treisman, A., and Burkell, J. (1983). The cost of visual filtering. *J. Exp. Psychol. Hum. Percept. Perform.* 9, 510–522. doi: 10.1037/0096-1523.9.4.510

Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. *J. Exp. Psychol. Hum. Percept. Perform.* 21, 451–468. doi: 10.1037/0096-1523.21.3.451

Lavie, N. (2000). "Selective attention and cognitive control: dissociating attentional functions through different types of load," in *Attention and Performance*, Vol. XVIII, eds S. Monsell and J. Driver (Cambridge, MA: MIT press), 175–194.

Lavie, N. (2005). Distracted and confused?: selective attention under load. *Trends Cogn. Sci.* 9, 75–82. doi: 10.1016/j.tics.2004.12.004

Lavie, N., and Cox, S. (1997). On the efficiency of attentional selection: efficient visual search results in inefficient rejection of distraction. *Psychol. Sci.* 8, 395–398. doi: 10.1111/j.1467-9280.1997.tb00432.x

Lavie, N., and Fox, E. (2000). The role of perceptual load in negative priming. *J. Exp. Psychol. Hum. Percept. Perform.* 26, 1038–1052. doi: 10.1037/0096-1523.26.3.1038

Lavie, N., and DeFokert, J. W. (2003). Contrasting effects of sensory limits and capacity limits in visual selective attention. *Percept. Psychophys.* 65, 202–212. doi: 10.3758/BF03194795

Lavie, N., and Tsal, Y. (1994). Perceptual load as a major determinant of the locus of selection in visual attention. *Percept. Psychophys.* 56, 183–197. doi: 10.3758/BF03213897

Leber, A. B., and Egeth, H. E. (2006). It's under control: top-down search strategies can override attentional capture. *Psychon. Bull. Rev.* 13, 132–138. doi: 10.3758/BF03193824

McDonald, J. J., Green, J. J., Jannati, A., and DiLollo, V. (2013). On the electrophysiological evidence for the capture of visual attention. *J. Exp. Psychol. Hum. Percept. Perform.* 39, 849–860. doi: 10.1037/a0030510

Miller, J. (1987). Priming is not necessary for selective-attention failures: semantic effects of unattended, unprimed letters. *Percept. Psychophys.* 41, 419–434. doi: 10.3758/BF03203035

Pannebakker, M. M., Jolicoeur, P., van Dam, W. O., Band, G. P. H., Ridderikhof, R., and Hommel, B. (2011). Mental rotation impairs attention shifting and short-term memory encoding: neurophysiological evidence against the response-selection bottleneck model of dual-task performance. *Neuropsychologia* 49, 2985–2993. doi: 10.1016/j.neuropsychologia.2011.06.021

Ruthruff, E., Miller, J., and Lachman, T. (1995). Does mental rotation require central mechanisms? *J. Exp. Psychol. Hum. Percept. Perform.* 21, 552–570. doi: 10.1037/0096-1523.21.3.552

Schreij, D., Owens, C., and Theeuwes, J. (2008). Abrupt onsets capture attention independent of top-down control settings. *Percept. Psychophys.* 70, 208–218. doi: 10.3758/PP.70.2.208

Theeuwes, J. (1992). Perceptual selectivity for color and form. *Percept. Psychophys.* 51, 599–606. doi: 10.3758/BF03211656

Theeuwes, J. (1994). Stimulus-driven capture and attentional set: selective search for color and visual abrupt onsets. *J. Exp. Psychol. Hum. Percept. Perform.* 20, 799–806. doi: 10.1037/0096-1523.20.4.799

Theeuwes, J. (1995). "Perceptual selectivity for color and form: on the nature of the interference effect," in *Converging Operations in the Study of Visual Attention*, eds A. F. Kramer, M. G. H. Coles, and G. D. Logan (Washington, DC: American Psychological Association), 297–314. doi: 10.1037/10187-010

Theeuwes, J. (1996). "Perceptual selectivity for color and form: on the nature of the interference effect," in *Converging Operations in the Study of Visual Attention*, eds A. F. Kramer, M. G. H. Coles, and G. D. Logan (Washington: American Psychological Association), 297–314.

Theeuwes, J. (2004). Top-down search strategies cannot override attentional capture. *Psychon. Bull. Rev.* 11, 65–70. doi: 10.3758/BF03206462

Theeuwes, J. (2010). Top-down and bottom-up control of visual selection. *Acta Psychol.* 123, 77–99 doi: 10.1016/j.actpsy.2010.02.006

Theeuwes, J., and Burger, R. (1998). Attentional control during visual search: The effect of irrelevant singletons. *J. Exp. Psychol. Hum. Percept. Perform.* 24, 1342–1353. doi: 10.1037/0096-1523.24.5.1342

Treisman, A. (1969). Strategies and models of selective attention. *Psychol. Rev.* 76, 282–299. doi: 10.1037/h0027242

Treisman, A., and Gelade, G. (1980). A feature integration theory of attention. *Cogn. Psychol.* 12, 97–136. doi: 10.1016/0010-0285(80)90005-5

Tsal, Y., and Benoni, H. (2010). Diluting the burden of load: perceptual load effects are simply dilution effects. *J. Exp. Psychol. Hum. Percept. Perform.* 36, 1645–1656. doi: 10.1037/a0018172

Wilson, D. E., Muroi, M., and MacLeod, C. M. (2011). Dilution, not load, affects distractor processing. *J. Exp. Psychol. Hum. Percept. Perform.* 37, 319–335. doi: 10.1037/a0021433

Wyble, B., Folk, C. L., and Potter, M. (2013). Contingent attentional capture by conceptually relevant images. *J. Exp. Psychol. Hum. Percept. Perform.* 39, 861–871. doi: 10.1037/a0030517

Yantis, S., and Johnston, J. C. (1990). On the locus of visual selection: evidence from focused attention tasks. *J. Exp. Psychol. Hum. Percept. Perform.* 16, 135–149. doi: 10.1037/0096-1523.16.1.135

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Detection is unaffected by the deployment of focal attention

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There has been much debate regarding how much information humans can extract from their environment without the use of limited attentional resources. In a recent study, Theeuwes et al. (2008) argued that even detection of simple feature targets is not possible without selection by focal attention. Supporting this claim, they found response time (RT) benefits in a simple feature (color) detection task when a target letter's identity was repeated on consecutive trials, suggesting that the letter was selected by focal attention and identified prior to detection. This intertrial repetition benefit remained even when observers were required to simultaneously identify a central digit. However, we found that intertrial repetition benefits disappeared when a simple color target was presented among a heterogeneously (rather than homogeneously) colored set of distractors, thus reducing its bottom–up salience. Still, detection performance remained high. Thus, detection performance was unaffected by whether a letter was focally attended and identified prior to detection or not. Intertrial identity repetition benefits also disappeared when observers were required to perform a simultaneous, attention-demanding central task (Experiment 2), or when unfamiliar Chinese characters were used (Experiment 3). Together, these results suggest that while shifts of focal attention can be affected by target salience, by the availability of excess cognitive resources, and by target familiarity, detection performance itself is unaffected by these manipulations and is thus unaffected by the deployment of focal attention.

Keywords: focal attention, perception, salience, locus of selection, priming

Humans often need to extract information from a complex visual world in order to accomplish behavioral goals. Attentional mechanisms provide one solution to this problem, allowing observers to select a subset of information from their surrounding environment for more detailed processing. However, in some cases information may be accessible without the use of limited attentional resources. In the present paper, we will consider whether simple feature targets can be detected without the deployment of focal attention.

There is a long-standing debate regarding the locus of the selection process. Early selection proponents (Broadbent, 1958; Treisman, 1964; Neisser, 1967) argue that only a very limited amount of information is available prior to selection. Late selection proponents (Cherry, 1953; Deutsch and Deutsch, 1963; Allport, 1977) argue that more detailed processing, such as semantic encoding, may occur in the absence of attention. More recent models suggest that the locus of selection may be flexible; for example, the demands of the task may determine the locus of selection (e.g., Yantis and Johnston, 1990). The perceptual load of the display may also affect the locus of selection (e.g., Lavie et al., 2004), although an alternative "dilution" account may explain these perceptual load effects (e.g., Tsal and Benoni, 2010).

Even strict early selection models of attention allow for some "preattentive" processing (e.g., Treisman and Gelade, 1980) in which some basic, low-level information is processed without the use of limited attentional resources. This preattentively acquired information is then available for use during subsequent cognitive processes. For example, when observers search for a target defined by one or more known properties, such as color, information from preattentive processing may be used to guide that selection process (e.g., Treisman and Sato, 1990; Wolfe, 1994; see Wolfe, 2007 for a more detailed description of guidance).

While most models of attention agree that some information is encoded preattentively, there is less consensus regarding whether observers have direct access to that information. According to Treisman and Gelade's (1980) Feature Integration Theory (FIT), individual "feature maps" register the presence of individual low-level features (e.g., color) rapidly and efficiently throughout the entire visual field. Observers can directly access these feature maps to detect a signal indicating the presence of a given feature. This direct access allows for detection of simple feature targets without needing to select those targets with a focal shift of spatial attention. Some data have supported this theory by demonstrating that detection of singleton targets (e.g., Braun and Sagi, 1990; Braun and Julesz, 1998; but see Joseph et al., 1997) or simple feature targets (e.g., Luck and Ford, 1998) is unaffected when a secondary, attention-demanding task is added concurrently with a primary task.

The Guided Search model of attention (Wolfe, 1994) is a proposed alternative to FIT. According to this model, feature maps are combined into an activation map, and attention is directed to the location with the greatest signal in that activation map. Therefore, even in an efficient search, focal attention must be directed to the location of the target prior to detection of that target by the observer. There is empirical support for the Guided Search model as well (e.g., Joseph et al., 1997; Kim and Cave, 1995). For example, Joseph et al. (1997) found that performance on a singleton detection task suffered when it was presented during an "attentional blink" (AB) period. The AB is a period of time after one target is presented in a central stream when attentional resources are diverted, thus making processing of a second target more difficult (e.g., Chun and Potter, 1995). Joseph et al.'s result thus suggests that attentional resources are necessary even for a simple pop-out detection task (but see Egeth et al., 2008, for conflicting results). However, an alternative account of the AB suggests it may reflect active suppression of incoming visual input rather than an absence of attentional resources (Olivers and Meeter, 2008), meaning that Joseph et al.'s results may be attributable to an active suppression process.

A NEW METHOD

In a recent study by Theeuwes et al. (2008), participants were asked to report whether a single red letter was present among a ring of otherwise gray letters. Participants responded more quickly when the identity of the target letter was repeated than when it was not. This is consistent with previous studies demonstrating that repetition of the identity of an attended stimulus can speed processing of that stimulus, even when identity is not task-relevant (e.g., Huang et al., 2004). Thus, participants must have processed the identity of the target letter at some level prior to executing a response indicating its presence. This effect persisted even when participants were required to identify a centrally presented digit, a task intended to tax attentional resources.

Critically, repetition of the identity of non-target letters had no effect on responses (for example, if a non-target gray "W" became the red target "W" on the next trial). This suggested that the identity of each and every individual letter was not available preattentively. The implication is that participants processed the identity of the target letter by selecting that letter with focal attention. Therefore, intertrial identity repetition benefits could only occur if the target letter was selected by focal attention, and thus identified, prior to the detection response. The authors concluded that this shift of focal attention was a necessary precondition for detection of the target letter.

THE PRESENT STUDY

Theeuwes et al. (2008) assumed that because a shift of attention occurred prior to the detection response, attention is a necessary precursor of detection. However, another possibility is that shifts of focal attention may have occurred but they may be unrelated to detection. That is, whether and when a shift of focal attention occurs may not affect detection performance, suggesting that detection relies on an independent mechanism. In the present study, we examine this possibility by applying the method of Theeuwes et al. (2008) to various simple feature target detection tasks in which deployment of focal attention is affected by manipulation of stimulus properties and task demands. We assess deployment of focal attention via intertrial repetition effects, and determine whether detection performance is affected by whether intertrial repetition benefits occur.

EXPERIMENT 1

In Theeuwes et al. (2008), the target, if present, was a color singleton. The authors concluded that focal attention is a necessary precursor of detection of simple feature targets. However, bottom–up salient items, such as color singletons, have been shown in some cases to capture attention regardless of an observer's intentions (e.g., Theeuwes, 1991; Bacon and Egeth, 1994, Experiment 1). Therefore, the deployment of focal attention may have occurred because of the target's bottom–up salience, and not because attention is required for detection.

In Experiment 1, we varied the bottom–up salience of the target by manipulating the color heterogeneity of the display; while singleton targets presented among a homogeneous set of distractors provide a strong bottom–up signal that can bias attention, no item provides a strong bottom–up signal (or "pops out") in a heterogeneously colored display (e.g., Duncan and Humphreys, 1989; Wolfe, 1992, 1994). We conducted a separate pilot study which confirmed that search times for the target were efficient even when the target was not a color singleton[1], as would be expected in a simple feature search task (e.g., Duncan, 1989; Duncan and Humphreys, 1989; Wolfe, 1994). However, in the non-singleton-target condition the bottom–up salience of the target was considerably reduced, and thus the target was unlikely to capture attention in a purely bottom–up manner. This design allowed us to explore the possibility that the repetition effects in Theeuwes et al.'s study occurred because the target automatically captured attention due to its bottom–up salience, and not because focal attention necessarily precedes detection.

METHODS

Participants

Thirty-two Johns Hopkins University undergraduate students (mean age = 19.8 years; 18 male) with normal or corrected-to-normal visual acuity and normal color vision participated for course credit in sessions lasting 30 min. Participants gave informed consent, and the protocol was approved by the Johns Hopkins Homewood Institutional Review Board.

Apparatus

Stimulus presentation and data analysis were performed using programs written in Matlab (Mathworks) and using PsychToolbox software (Brainard, 1997).

[1]In a separate study, we varied the number of items on a trial-by-trial basis (2, 4, or 8). Fourteen participants searched for a red target among heterogeneously colored displays similar to those described in the methods section of Experiment 1. We found minimal costs in RT on target-present trials with increasing set size (369, 370, and 380 ms, respectively; slope = 1.9 ms/item). The effect of display size was not significantly different from 0, $F_{(2, 26)} = 1.68$, $p > 0.1$. This result is in line with several previous studies showing minimal search slopes for detection of a simple color target in a heterogeneous display (e.g., Duncan, 1989; D'Zmura, 1991; Bauer et al., 1996).

Stimuli

On each trial, 8 English letters appeared, arranged in a circle surrounding the center of the display. At a viewing distance of 42 cm, each letter subtended a visual angle of 1°, and the radius of the circle that the letters formed subtended 6.35° of visual angle.

Following Theeuwes et al. (2008), participants had to indicate with a key press whether or not a red target letter was present. Each trial was randomly assigned as either target present or target absent. In the singleton-target condition, all seven non-target letters were colored white. In the non-singleton-target condition, non-target letters were heterogeneously colored, consisting of a combination of white, green, blue, pink, and yellow letters (see **Figure 1**). A white digit (1–8) obscured by dots (as in Theeuwes et al., 2008) appeared on each trial in all conditions at fixation, subtending 1° of visual angle. However, participants were instructed to ignore the central number (it was present as a perceptual control for an alternate set of experiments not reported in the present paper).

Design and procedure

Participants were randomly assigned to either the singleton-target or non-singleton-target condition for the duration of the experiment. Each trial began with a display of a white fixation cross at the center of the screen subtending 1° of visual angle for 1 s. Following this, the primary stimulus display featuring the digit at the center and 8 English letters in a circular array surrounding the center appeared for 120 ms. Participants subsequently indicated whether or not a red letter had been present with a keypress ("z" for present, "x" for absent). There was a 500 ms intertrial interval during which a blank black screen was presented.

When a red target letter was present on consecutive trials (roughly 25% of all trials), there was a 50% chance the target letter identity was repeated. Therefore, ~12.5% of all trials included a repeated target letter. There were 10 blocks of 64 trials each in the experiment, the first of which was a practice block.

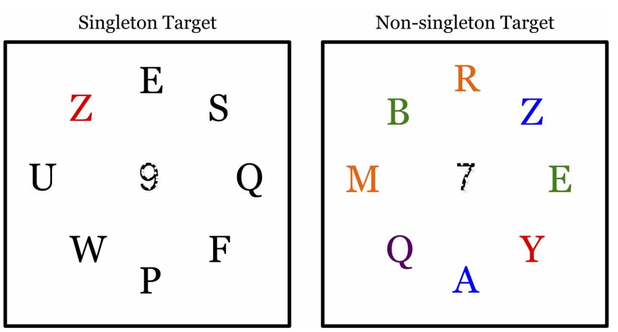

FIGURE 1 | In both conditions, participants indicated the presence or absence of a red letter. In the singleton-target condition, all remaining letters were colored white on a black background (black and white are reversed in the figures for clarity). In the non-singleton-target condition, the remaining letters were heterogeneously colored. The display was on for 120 ms.

RESULTS AND DISCUSSION

We eliminated all responses faster than 100 ms and subsequently used a modified recursive trimming procedure (Van Selst and Jolicoeur, 1994) to remove outliers in each experimental condition. This resulted in an elimination of 1.2% of all trials. All error trials were removed for response time (RT) analysis (3% of all trials). Because we were comparing intertrial effects resulting from repeated target properties, the following analyses only include trials where a target was present on consecutive trials (i.e., trials *N-1* and *N*) and the observers' response on the previous trial (i.e., on trial *N-1*) was correct.

We conducted a 2 × 2 mixed-design ANOVA with a between-subjects factor of target type (singleton vs. non-singleton) and a within-subjects factor of target identity repetition (identity repeated vs. not repeated) for measures of error rate (ER) and RT. Performance accuracy was high overall (97%).

There was no main effect of target type on RT or ER ($ps > 0.1$). Thus, the bottom–up salience of the target did not impact overall detection performance. There were no main effects or interactions for ER on any analyses; thus, the rest of the section focuses on RT measures only (ERs for this and subsequent experiments are reported in **Table 1**).

If focal attention necessarily precedes detection in a fixed manner, letter identification likely also occurs prior to detection (as in Theeuwes et al., 2008), and we would expect a main effect of target identity repetition. However, there was no main effect of target identity repetition, $F_{(1, 30)} < 1$. There was, however, an interaction between target type and target identity repetition, $F_{(1, 30)} = 5.68$, $p < 0.05$ (**Figure 2**). We conducted simple main effects analyses to interpret this interaction.

In the singleton-target condition, responses were significantly faster when the target was repeated (334 ms) than when the target identity was not repeated (347 ms), $F_{(1, 15)} = 5$, $p < 0.05$, replicating (Theeuwes et al., 2008) and suggesting that the target

Table 1 | Error rates across all experiments.

Experiment	Identity repeated	Identity not repeated	Overall performance
Experiment 1			
Singleton condition	3.55	3.53	2.62
Non-singleton condition	2.42	3.37	3.32
Experiment 2	3.1	3.59	4.13
Experiment 3A	1.25	2.27	2.12
Experiment 3B			
English letters	2.15	4.21	3.44
Chinese letters	1.11	2.97	2.9

Percentage error rates for all experimental conditions in all three experiments (first two columns), and overall error rates for all three experiments (third column). Overall error rates calculated across all trials in a given experiment (or language type, in the case of Experiment 3B) regardless of whether target presence, identity, or language type was repeated across trials. Because this includes many trials that were not included in calculations of identity repeated and identity not repeated trials, this number does not necessarily equal the mean of the error rates in those two conditions.

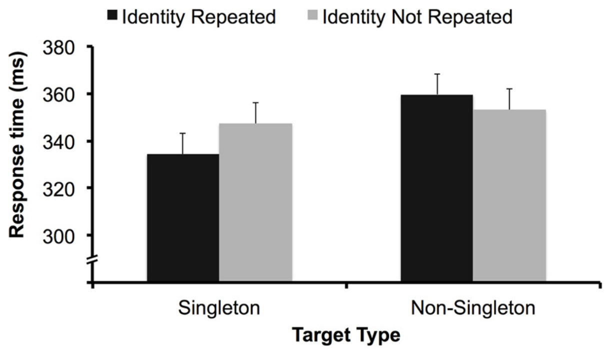

FIGURE 2 | Data from Experiment 1. Participants responded more quickly when the target letter identity was repeated in the singleton-target condition. There was no effect of target identity repetition in the non-singleton-target condition. Error bars represent 95% confidence intervals for the singleton-target condition and non-sinlgeton-target conditions separately. (e.g., Loftus and Masson, 1994).

letter was selected by focal attention prior to the execution of a detection response in this condition. In a separate analysis, we found there was no effect of a non-target letter on the previous trial becoming the target on the current trial (also replicating Theeuwes et al., 2008), $F_{(1, 15)} < 1$. This demonstrates that participants were not identifying all the letters on the screen preattentively, but instead only processing the identity of the target letter after selecting that letter with focal attention.

In the non-singleton-target condition, there was no benefit to repeating target identity; instead, responses were numerically *slower* in trials where target identity was repeated (360 ms) vs. when it was not (353 ms), though this 7 ms difference did not approach significance, $F_{(1, 15)} = 1.28$, $p > 0.1$. Thus, when the target was not a color singleton, the identity of the target letter was *not* fully processed prior to execution of a detection response.

From these results, we can conclude that the selection process itself must have differed between the two conditions even though detection performance did not (no overall difference in RT or ER). Although a null result cannot be taken as definitive evidence, the data nonetheless suggest that the target letter was not selected by focal attention prior to detection in the non-singleton-target condition. We discuss more detailed theoretical accounts of these data in the discussion; however, what these data unambiguously show is that the process of detecting a simple feature target is not affected by changes in the deployment of focal attention. Therefore, it may be the case that focal attention is not a necessary precondition for simple feature target detection, and Theeuwes et al.'s results may instead be explained by the target's bottom–up salience.

EXPERIMENT 2

In Luck and Ford (1998), as well as in Theeuwes et al. (2008), participants had to identify a central digit obscured by dots while also performing a simple detection task. By adding a difficult second task at the center of the screen, the authors of those studies reasoned that participants would no longer have excess attentional resources available to devote to the simple feature detection task. Luck and Ford (1998) found that the N2PC disappeared when the second central task was added, leading them to conclude that focal attention was not necessary for the feature detection task, as it was in evidence only when there were no other demands on attention. Theeuwes et al. (2008), on the other hand, found that adding a central task had no effect on intertrial facilitation when the identity of the target character was repeated, suggesting that focal attention was still directed to the peripheral target even when attentional resources were being taxed by the central task.

However, it is possible that a number obscured by dots was not the ideal secondary task to sufficiently tax attentional resources. The presence of obscuring dots imposes a data limitation on processing (cf. Norman and Bobrow, 1975), meaning that additional attentional resources might not overcome the lack of sensory information coming from the letter. In data-limited tasks like this, participants may not devote additional attentional resources to the digit if they are having trouble identifying it because doing so will not improve their performance.

In Experiment 2, we introduced a "resource-limited" central task instead in order to more effectively tax attentional resources. In resource-limited tasks, task difficulty *can* be overcome with the use of additional attentional resources (cf. Norman and Bobrow, 1975). Thus, inclusion of a resource-limited task would increase the load on available cognitive resources, potentially eliminating an unnecessary shift of attention in the detection task. We had participants search for a rotated "T" among rotated "L"s near the center of the screen while simultaneously determining whether a simple feature target was present. This type of spatial-configuration task was shown to be attentionally demanding by Huang and Pashler (2005), and thus could be described as a "resource-limited" task.

METHODS

Thirty-two Johns Hopkins University undergraduate students (mean age = 19.3 years; 13 male) with normal or corrected-to-normal visual acuity and normal color vision participated in sessions for course credit lasting 30–60 min. Participants gave informed consent, and the protocol was approved by the Johns Hopkins Homewood Institutional Review Board.

The peripheral task was identical to the singleton-target condition in Experiment 1. In addition, at a random location inside an imaginary circle with a radius of 3.22° of visual angle surrounding the center of the screen, there was a single rotated "T" subtending 0.28° of visual angle. There were between 1 and 4 rotated "L"s present in the circle as well. The number of "L"s was kept consistent throughout a block, and there were two blocks each of the four possible numbers (1, 2, 3, or 4), of distractor "L"s resulting in 8 total blocks of trials, preceded by one practice block with two distractor "L"s. The order of blocks was assigned randomly across participants. Each "L" was the same size as the "T," taking up 0.28° of visual angle. All items were displayed on the screen for 120 ms (see **Figure 3**).

Participants first responded to the presence or absence of red by pressing either the "z" key or the "x" key with their left

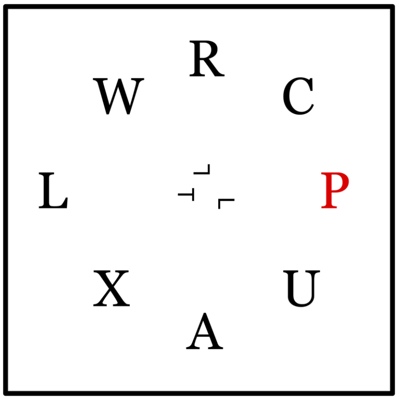

FIGURE 3 | After indicating the presence or absence of a red letter, participants were required to report the orientation of a rotated "T" presented among rotated "L"s in the center of the display (the "T" was either facing left or facing right). The second response was untimed. The display was on for 120 ms.

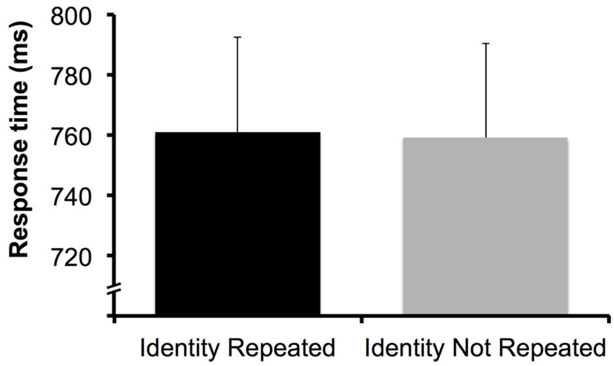

FIGURE 4 | Data from Experiment 2. There was no effect of target identity repetition. Error bars represent 95% confidence interval (e.g., Loftus and Masson, 1994).

hand. Following that, participants were told to indicate which direction the "T" was pointing, either to the right or to the left. Using the number pad with their right hand, participants pressed the "4" key if the "T" was pointing left, and the "6" key if it was pointing right. Participants were encouraged to make a speeded response to the presence or absence of red, but they were told that their response to the orientation of the "T" was an untimed response. There were 9 blocks of 64 trials each in the experiment, the first of which was a practice block.

RESULTS AND DISCUSSION

We eliminated all responses faster than 100 ms and subsequently used a modified recursive trimming procedure (Van Selst and Jolicoeur, 1994) to remove outliers in each experimental condition. This resulted in an elimination of 0.6% of all trials. Because we were comparing intertrial effects resulting from repeated target properties, the following analyses only include trials where a target was present on consecutive trials, the observers' response to the peripheral task was correct on the previous trial was correct, and the observers' response to the central task on both the previous and current trial was correct. Additionally, all error trials from the peripheral task (4.1% of all trials) were removed from RT analyses. Performance on the central task was 83.7% overall. This was comparable to previous studies using a central task to tax attentional resources (Luck and Ford, 1998; Theeuwes et al., 2008).

Participants still performed very well on the primary task (the detection of the red target), answering correctly on 95.9% of all trials. In a one-way ANOVA comparing accuracy across the two conditions of Experiment 1 and the present experiment as a third condition, there was no main effect of condition on accuracy, $F_{(2, 61)} = 1.55$, $p > 0.1$. Thus, performance accuracy on the detection task was not statistically worse when a secondary, resource-demanding central task was added to the display.

We conducted a one-way ANOVA with a within-subject factor of target identity repetition (identity repeated vs. not repeated) for measures of ER and RT. RT was practically identical whether or not the target identity was repeated (761 ms for repeated, 759 for non-repeated), $F_{(1, 31)} < 1$ (**Figure 4**), and there was no effect of repeating target identity on ER (3.1% for repeated, 3.3% for non-repeated), $F_{(1, 31)} < 1$. Unlike in Theeuwes et al. (2008), the addition of a central task eliminated intertrial facilitation effects. This difference in outcomes is likely attributable to the use of a resource-limited task in the present experiment, which depleted available attentional resources more successfully than the number obscured by dots used by Luck and Ford (1998) and Theeuwes et al. (2008).

One possible concern is that the target's identity was processed prior to detection, but that target repetition benefits dissipated because RTs were long overall compared to the first experiment. Theeuwes et al. (2008) found repetition priming effects in a dual-task experiment with long RTs, but the RTs in that study were around 160 ms shorter on average than the RTs in the present experiment (~600 vs. ~760 ms). Other studies, however, have found target repetition benefits for RTs longer than those observed in the present study (e.g., Fecteau, 2007 found priming effects for RTs ~900 ms), and priming effects can persist over periods of time up to ~30 s or longer (e.g., Maljkovic and Nakayama, 1994). Thus, it is reasonable to expect that target repetition benefits might be observed for RTs as long as those found in the present study.

Nevertheless, we re-analyzed the results of the singleton target condition from Experiment 1 by separating the responses from each subject into RT deciles for each condition. This allowed us to determine whether target repetition effects diminished at longer RTs (**Figure 5A**). We conducted a 2 × 10 ANOVA with factors of target identity repetition (identity repeated vs. not repeated) and decile (1–10) on these RT data. There was an interaction between these two factors, $F_{(9, 135)} = 3.96$, $p < 0.001$, suggesting that the effect of target identity repetition did differ across decile. In **Figure 5A**, it appears that target repetition benefits do not diminish at longer RTs. If anything, target repetition benefits are larger in magnitude for longer RTs; for example, at deciles 8–10,

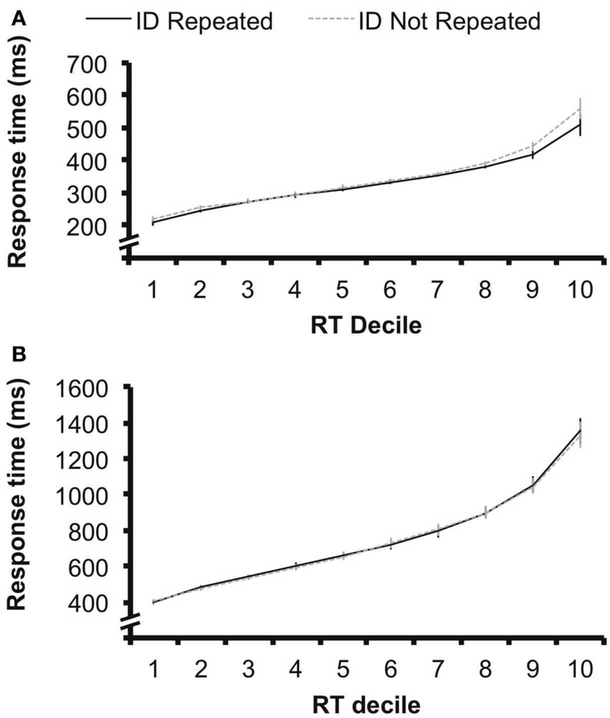

FIGURE 5 | (A) Data from the singleton-target condition of Experiment 1 sorted into response time deciles for the target identity repeated (ID Repeated) and target identity not repeated (ID Not Repeated), with the fastest 10% of responses in each condition in Decile 1, and the slowest 10% of responses in Decile 10. The magnitude of the priming benefit did not diminish in slower responses; instead, target identity repetition benefits were larger in magnitude in later deciles in which response times were slower. Error bars represent 95% confidence interval calculated separately for each decile (e.g., Loftus and Masson, 1994). **(B)** The same analysis applied to the data from Experiment 2. Target identity repetition benefits are not observed at any decile. Error bars represent 95% confidence interval calculated separately for each decile (e.g., Loftus and Masson, 1994).

the average target repetition benefit is 28 ms, while the magnitude of target repetition benefits at deciles 1–7 is 5 ms. A *post-hoc* contrast-contrast interaction analysis revealed that this comparison between the target repetition effect at deciles 1–7 vs. 8–10 was significant, $F_{(9, 135)} = 20.24$, $p < 0.001$. This analysis confirms that target repetition benefits were not diminished at longer RTs, but instead were more pronounced.

To further ensure that target letter identity effects were not obscured by longer RTs, we conducted the same decile analysis for the data from Experiment 2 (**Figure 5B**). We found no interaction between target identity repetition and decile, $F_{(9, 135)} < 1$, suggesting that even when RTs were comparable in length to those of Experiment 1 (mean RT in decile 1 = 400 ms), there was no effect of target identity repetition.

As with Experiment 1, we cannot definitively conclude from this null effect that attention was not shifted. Nevertheless, these data demonstrate that the inclusion of a resource-limited central task eliminated intertrial identity repetition effects, while detection performance remained high, providing converging evidence that detection performance is unaffected by shifts of focal attention.

EXPERIMENT 3A

Teichner and Krebs (1974) demonstrated that familiar characters may undergo "compulsive encoding," meaning that they are automatically processed regardless of the task goals of the observer. It could therefore be the case that the use of familiar characters in Theeuwes et al. (2008) biased observers to compulsively encode the target letter, which required a shift of focal attention. In Experiment 3A, we replaced all familiar English characters with unfamiliar Chinese characters while still using singleton targets, to determine whether intertrial repetition of the character identity will still lead to a benefit in RTs if we reduce the likelihood of "compulsive encoding." If the use of unfamiliar Chinese characters eliminated intertrial target repetition benefits, this would provide converging evidence that detection performance is unaffected by shifts of focal attention.

METHODS

Sixteen Johns Hopkins University undergraduate students (mean age = 19.7 years; 11 male) with normal or corrected-to-normal visual acuity and normal color vision participated in sessions lasting 30–60 min. Participants received extra credit in undergraduate courses as compensation. Participants gave informed consent, and the protocol was approved by the Johns Hopkins Homewood Institutional Review Board.

In Experiment 3A, Chinese characters were used instead of English letters. These characters came from the "Yung" Chinese font (Pelli et al., 2006). In all other respects, Experiment 3A was identical to the singleton-target condition of Experiment 1 (see **Figure 1**). Participants were given a questionnaire regarding the English translations of the Chinese characters at the conclusion of the experiment in order to assess the participants' Chinese reading comprehension skills. The one participant who was able to identify a subset of the characters was replaced. In all other respects, the design was identical to Experiment 1.

RESULTS AND DISCUSSION

We eliminated all responses faster than 100 ms and subsequently used a modified recursive trimming procedure (Van Selst and Jolicoeur, 1994) to remove outliers in each experimental condition. This resulted in an elimination of 1.2% of all trials. All error trials were removed for RT analysis (2.1% of all trials). Because we were comparing intertrial effects resulting from repeated target properties, the following analyses only include trials where a target was present on consecutive trials and the observers' response on the previous trial was correct. Performance accuracy was again high (97.9%).

We conducted a one-way ANOVA with a within-subject factor of target identity repetition (identity repeated vs. not repeated) for measures of ER and RT. Again, there was no significant effect of target repetition on RT (347 ms for repetition trials, 346 ms for non-repetition trials), $F_{(1, 15)} < 1$ (**Figure 6A**), or ER (1.2% for repetition trials, 2.3% for non-repetition trials), $F_{(1, 15)} = 3.24$, $p > 0.09$. As in Experiment 2, this is a case where a singleton target was easily detected but did not result in repetition priming,

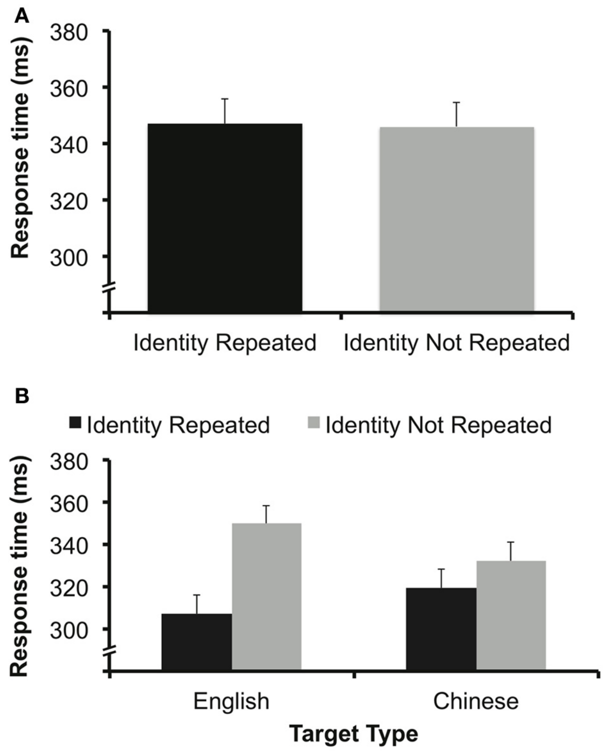

FIGURE 6 | (A) Data from Experiment 3A. There was no effect of target identity repetition. Error bars represent 95% confidence interval (e.g., Loftus and Masson, 1994). **(B)** Data from Experiment 3B. There was a benefit to repeating target identity for both English letters and Chinese letters. Error bars calculated from a within-subjects interaction error term (e.g., Loftus and Masson, 1994).

suggesting a dissociation between the process related to detection and those related to shifts of focal attention that elicit repetition priming effects.

We note the possibility that the target identity repetition benefits observed in the singleton condition of Experiment 1 and Theeuwes et al. (2008) could reflect semantic priming rather than perceptual priming. If that were the case, we would not expect priming to occur in the present study regardless of whether observers shifted focal attention to the target or not, because the characters used in the present study had no semantic association.

A study by Petit et al. (2006) used electroencephalographic measures to determine the time-course of single letter priming effects examining both visual similarity and case-independent letter identity. Petit et al. found that visual similarity to a previous letter affected the electrophysiological response much earlier in time (120–180 ms) than case-independent letter identity effects (220–300 ms). Eddy et al. (2006) found similar evidence for early modulation of electrophysiological responses based on shared perceptual properties using non-letter object stimuli. Thus, it seems likely that target identity repetition effects observed in the present study and Theeuwes et al. (2008) are attributable at least in part to perceptual priming. Still, further studies would be necessary to rule out entirely the possibility that the target identity repetition effects observed in Experiment 1 and Theeuwes et al. (2008) were due to semantic priming alone.

EXPERIMENT 3B

In Experiment 3A, it is possible that focal attention was directed to the letter, but because of the complexity of the Chinese characters we used, participants were unable to fully process the identity of the stimuli. Perhaps the Chinese characters used in this experiment were equivalent for our participants to the "impossible objects," used by Schacter et al. (1990). In that study, participants had to determine whether presented objects could possibly exist in 3-dimensional space, and there was no benefit for repeating impossible objects on consecutive trials. Had we used impossible objects as the red target, participants might have shifted focal attention to the impossible object target, but we would not observe intertrial facilitation when the same impossible object was repeated. We would therefore not be able to use that lack of intertrial priming to conclude anything about focal attention.

To address this possible confound, we ran an additional experiment in which participants saw a single letter presented at the center of the screen, and were asked to identify whether the letter was an English letter or not. The purpose of this experiment was to determine whether any intertrial facilitation was possible with unfamiliar Chinese characters in our subject population.

METHODS

Sixteen Johns Hopkins University undergraduate students (mean age = 19.8 years; 5 male) with normal or corrected-to-normal visual acuity and normal color vision participated in sessions lasting 30–60 min. Participants received extra credit in undergraduate courses as compensation. Participants gave informed consent, and the protocol was approved by the Johns Hopkins Homewood Institutional Review Board.

Participants indicated whether a centrally presented white character was in English or Chinese with a button press. They pressed the "z" key if it was English and the "x" key if it was not English. Non-English letters were always Chinese characters. The letter subtended 1° of visual angle, and was presented for 120 ms. When the language of the letter was the same on consecutive trials (which was the case 50% of the time), the identity of the letter was repeated 50% of the time. As in Experiment 3A, participants were given a questionnaire regarding the English translations of the Chinese characters at the conclusion of the experiment in order to assess the participants' Chinese reading comprehension skills, and only participants who did not correctly identify any of the Chinese characters were included in the study. There were 10 blocks of 64 trials each in the experiment, the first of which was a practice block.

RESULTS AND DISCUSSION

We eliminated all responses faster than 100 ms and subsequently used a modified recursive trimming procedure (Van Selst and Jolicoeur, 1994) to remove outliers in each experimental condition. This resulted in an elimination of 1% of all trials. All error trials were removed for RT analysis (3% of all trials). Because we were comparing intertrial effects resulting from repeated target properties, the following analyses only include trials where the language of the target was repeated on consecutive trials, and the observers' response on the previous trial was correct.

We performed a 2 × 2 ANOVA with within-subjects factors of character language (English or Chinese) and target identity repetition (identity repeated vs. not repeated) for measures of ER and RT. There was no main effect of language on RT, $F_{(1, 15)} < 1$, or ER, $F_{(1, 15)} = 2.8$, $p > 0.1$. There was a main effect of repeating the identity of the character on both RT, $F_{(1, 15)} = 48.12$, $p < 0.001$, and ER, $F_{(1, 15)} = 22.06$, $p < 0.001$. RT was faster (313 vs. 341 ms) and participants made fewer errors (1.6 vs. 3.6%) when the identity of the target was repeated. There was also a significant interaction between character language and target identity repetition for RT, $F_{(1, 15)} = 12.75$, $p < 0.01$ (**Figure 6B**). There was a greater RT benefit when an English character was repeated (43 ms) than when a Chinese character was repeated (13 ms). There was no interaction for ER, $F_{(1, 15)} < 1$.

We analyzed target identity repetition benefits for the different languages separately with simple main effects analyses. The benefit of repeating the target character on RT was significant for both English characters (307 vs. 350 ms), $F_{(1, 15)} = 54.39$, $p < 0.001$, and Chinese characters (319 vs. 332 ms), $F_{(1, 15)} = 4.9$, $p < 0.05$. The benefit for ER was significant for English characters (2.1 vs. 4.2%), $F_{(1, 15)} = 10.62$, $p < 0.01$ and for Chinese characters (1.1 vs. 3%), $F_{(1, 15)} = 8.65$, $p < 0.05$.

This task differed from the task in Experiment 3A in that observers were indicating the language of the letter, the letter was presented centrally rather than peripherally, and the location of the letter (at fixation) was known in advance of each trial. Therefore, we cannot be certain that these results would generalize to the display characteristics of Experiment 3A. Nevertheless, these results demonstrate that some type of priming is possible with unfamiliar Chinese characters, suggesting that the characters are not so complex as to preclude any form of priming. Therefore, these results suggest that the complexity of the characters *per se* is likely not responsible for the lack of intertrial facilitation observed in Experiment 3A.

GENERAL DISCUSSION

Repeating the identity of a color singleton target letter on consecutive trials sped detection RT, replicating the results of Theeuwes et al. (2008). This suggests that focal attention was directed to the target letter, allowing identification of that letter before execution of the detection response. However, this repetition benefit disappeared when the target letter was not a color singleton, while detection performance remained high. The target identity repetition benefit also disappeared in the singleton feature target detection task when participants were required to perform a simultaneous resource-limited central task (Experiment 2) and when the English letters were replaced with unfamiliar Chinese characters (Experiment 3).

Target identity repetition effects changed across the different conditions in three experiments, even though the target-defining feature was identical in all conditions. Thus, disparities emerged only because of changes in how focal attention was (or was not) deployed to the target letter, and the deployment of focal attention was determined by factors such as the perceptual salience of the target (Experiment 1), the availability of excess cognitive resources (Experiment 2), or the familiarity of the stimuli (Experiment 3). Together, these data demonstrate that detection performance was unaffected by changes in the deployment of focal attention. This suggests that detection occurred without the deployment of focal attention in the non-singleton condition of Experiment 1, and Experiments 2 and 3. However, proving a negative is difficult. Although we demonstrate converging evidence, we cannot with absolute certainly claim that detection occurs in the complete absence of focal attention based on these null results. Instead, in the following section, we consider how shifts of focal attention might differ depending on context, and how those differences relate to the detection process. This discussion focuses primarily on the salience manipulation from Experiment 1.

THE RELATIONSHIP BETWEEN FOCAL ATTENTION AND DETECTION

A singleton target is likely to have a stronger pull on attention than a non-singleton target because a singleton target conveys a more robust bottom–up signal to the observer's visual system (cf. Bravo and Nakayama, 1992). This might lead to differences in the selection process for each target by affecting the *speed* of the deployment of focal attention. In that case, the signal from a singleton target would pass a decision threshold more quickly than the signal from a non-singleton target, and a singleton target would be selected at an earlier point in time relative to its onset compared to a non-singleton target.

Additionally, the *strength* of the selection process following deployment of focal attention could be altered by target salience. That is, focal attention could be deployed to a target at roughly the same delay regardless of the target's bottom–up salience, but more attentional resources might be deployed when the target is a singleton. Subsequently, more information would be extracted from the target at a quicker pace immediately following selection when the target is a singleton rather than a non-singleton.

We can consider how these processes relate to the detection process in Experiment 1. One explanation for our results is that a shift of focal attention preceded detection whether the target was a color singleton or not, but that the selection process itself was robust enough to result in letter identification prior to detection only in the singleton-target condition of Experiment 1. This account would not be tenable if only the *speed* of deployment of focal attention differed between the two conditions, because if the selection process itself were the same between the two conditions once it reached the target, letter identification should precede color detection in both cases and overall RT would be slower in the non-singleton-target condition. However, neither of these results occurred. If the *strength* of selection differed between the two conditions, we would also have to conclude that changing the *strength* of the selection process influenced letter identification but not detection. Thus, detection and identification would constitute independent components of the selection process that are differentially affected when the strength of deployment changes.

A more parsimonious explanation of our results, which also fits well with the data from Experiments 2 and 3, is simply that detection occurs independently from focal attention, as proposed in FIT (Treisman and Gelade, 1980). When a target is defined by a single feature, deployment of attention to that target may depend on factors such as perceptual salience, availability of excess attentional resources, or the familiarity of the target. In some cases, selection occurs quickly and robustly enough to precede the detection process (as in the singleton-target condition, and Theeuwes et al., 2008), but this does not mean that selection always necessarily precedes detection. It is not surprising that focal attention would eventually be directed toward the target in the non-singleton-target condition in Experiment 1, for example, because excess attentional resources were likely available due to the simple nature of the task. Thus, we would infer that focal attention was likely deployed toward the target in the non-singleton-target condition, but that the detection process was completed independently and concluded before focal attention reached the target.

The latter interpretation is consistent with data from a recent study by Turatto et al. (2010). In that study, observers were presented with a ring of colored circles and cued to search for a particular target color on each trial. In the *detection task*, observers had to determine whether any of the circles matched the target color. In the *discrimination task*, observers had to indicate whether the letter inside one of the circles was a consonant or vowel. For both task types, there were three possible types of target-present displays: a color singleton target display (i.e., one of the circles matched the target color, and the remaining circles matched the distractor color), a color singleton distractor display (i.e., one of the circles matched the distractor color, and the remaining circles matched the target color), or a no-singleton display (all circles were target-colored).

Response times in the detection task were slowest when there was only one target (the color singleton target). On the other hand, RTs in the discrimination task were faster, and search slopes were shallower, on color singleton target displays compared to color singleton distractor displays, even though more target circles were present in the singleton distractor displays. Because the discrimination task requires processing of a letter stimulus at a specific location, a shift of focal attention is required. As expected, the data demonstrate that bottom–up salience influences this process, as RTs were faster when the target stimulus was salient in the discrimination task. However, in the detection task, salience was not a factor; instead, the number of target items determined how fast observers detected the presence of a target-colored circle. Thus, the data suggest that detection is not influenced by target selection, and instead that detection may occur without a shift of focal attention.

LETTER IDENTIFICATION WITHOUT A SHIFT OF FOCAL ATTENTION?

In the Singleton Condition of Experiment 1, we presumed that because we found intertrial identity repetition benefits, the target letter was selected following a shift of focal attention. However, the data from the present studies might be interpreted in the framework of other attention theories, such as load theory (e.g., Lavie, 1995) or dilution (e.g., Tsal and Benoni, 2010) that do not necessarily require a shift of focal attention for letter identification. Unfortunately, load and dilution studies have typically used tasks that require explicit identification of letters, rather than a color target detection task that we use here in which letter processing is likely implicit and is not task-relevant. Therefore, it is difficult to interpret exactly how load and dilution theories would be used to predict the current results. For example, it may be the case that the singleton-target condition of Experiment 1 reflected a reduced perceptual load or reduced dilution from non-target distractors relative to the non-singleton-target condition, thus explaining why the target letter's identity was processed before the detection response. On the other hand, the number of neutral distractor letters is identical in both conditions of Experiment 1, and previous studies supporting the dilution account (e.g., Benoni and Tsal, 2010; Tsal and Benoni, 2010) have suggested that the number of neutral distractor letters present is a determining factor in whether or not processing of the target's identity is affected by distractor presence.

Additional studies would be useful in addressing how the results of the current study might be informed by load and dilution theories, and might potentially challenge the claim that intertrial priming in the current paradigm reflects a shift of focal attention. However, even if the target repetition effects in the present study did not reflect a shift of focal attention, the results reported here would still demonstrate that changes in target salience, availability of excess cognitive resources, or target familiarity affect intertrial repetition priming effects without affecting detection performance. This demonstrates that the processes and resources involved in letter identification are not required for the detection of a simple feature target.

CONCLUSION

It has been argued that even a simple feature target can only be detected after that target has been selected by focal attention. Here we present new evidence that brings that claim into question. Specifically, in three experiments, we have shown that whether or not letter identity is processed before the detection response, a direct result of selection by focal attention, does not affect detection performance; therefore, there is a minimal or absent relationship between focal attention and simple feature detection. Instead, whether simple feature targets are selected prior to detection depends on factors such as the perceptual salience of the target (Experiment 1), the availability of excess cognitive resources (Experiment 2), and the familiarity of the target stimulus set (Experiment 3).

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REFERENCES

Allport, D. A. (1977). "On knowing the meaning of words we are unable to report: the effects of visual masking," in *Attention and Performance VI*, ed S. Dornic (Hillsdale, NJ: Erlbaum), 505–534.

Bacon, W. F., and Egeth, H. E. (1994). Overriding stimulus-driven attentional capture. *Percept. Psychophys.* 55, 485–496.

Bauer, B., Jolicoeur, P., and Cowan, W. B. (1996). Visual search for colour targets that are or are not linearly separable from distractors. *Vision Res.* 36, 1439–1466.

Benoni, H., and Tsal, Y. (2010). Where have we gone wrong? Perceptual load does not affect selective attention. *Vision Res.* 50, 1292–1298.

Brainard, D. (1997). The psychophysics toolbox. *Spat. Vis.* 10, 433–436.

Braun, J., and Julesz, B. (1998). Withdrawing attention at little or no cost: detection and discrimination tasks. *Percept. Psychophys.* 60, 1–23.

Braun, J., and Sagi, D. (1990). Vision outside the focus of attention. *Percept. Psychophys.* 48, 45–58.

Bravo, M., and Nakayama, K. (1992). The role of attention in different visual search tasks. *Percept. Psychophys.* 51, 465–472.

Broadbent, D. E. (1958). *Perception and Communication.* New York, NY: Pergamon Press.

Cherry, E. C. (1953). Some experiments on the recognition of speech, with one and two ears. *J. Acoust. Soc. Am.* 25, 975–979.

Chun, M. M., and Potter, M. C. (1995). A two-stage model for multiple target detection in rapid serial visual presentation. *J. Exp. Psychol. Hum. Percept. Perform.* 21, 109–127.

Deutsch, J. A., and Deutsch, D. (1963). Attention: some theoretical considerations. *Psychol. Rev.* 70, 80–90.

Duncan, J. (1989). Boundary conditions on parallel processing in human vision. *Perception* 18, 457–469.

Duncan, J., and Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychol. Rev.* 96, 433–458.

D'Zmura, M. (1991). Color in visual search. *Vision Res.* 31, 951–966.

Eddy, M., Schmid, A., and Holcomb, P. J. (2006). Masked repetition priming and event-related brain potentials: a new approach for tracking the time-course of object perception. *Psychophysiology* 43, 564–568.

Egeth, H. E., Leonard, C. J., and Palomares, M. (2008). The role of attention in subitizing: is the magical number 1? *Vis. Cogn.* 16, 463–473.

Fecteau, J. H. (2007). Priming of pop-out depends upon the current goals of observers. *J. Vis.* 7, 1–11.

Huang, L., Holcombe, A. O., and Pashler, H. (2004). Repetition priming in visual search: episodic retrieval, not feature priming. *Mem. Cogn.* 32, 12–20.

Huang, L., and Pashler, H. (2005). Attention capacity and task difficulty in visual search. *Cognition* 94, B101–B111.

Joseph, J., Chun, M., and Nakayama, K. (1997). Attentional requirementsina 'preattentive' feature searchtask. *Nature* 387, 805–807.

Kim, M., and Cave, K. (1995). Spatial attention in visual search for features and feature conjunctions. *Psychol. Sci.* 6, 376–380.

Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. *J. Exp. Psychol. Hum. Percept. Perform.* 21, 451–468.

Lavie, N., Hirst, A., De Fockert, J. W., and Viding, E. (2004). Load theory of selective attention and cognitive control. *J. Exp. Psychol. Gen.* 133, 339–354.

Loftus, G., and Masson, M. (1994). Using confidence intervals in within-subject designs. *Psychon. Bull. Rev.* 1, 476–490.

Luck, S., and Ford, M. (1998). On the role of selective attention in visual perception. *Proc. Natl. Acad. Sci.* 95, 825–830.

Maljkovic, V., and Nakayama, K. (1994). Priming of pop-out: I. Role of features. *Mem. Cogn.* 22, 657–672.

Neisser, U. (1967). *Cognitive Psychology.* New York, NY: Appleton-Century-Crofts.

Norman, D., and Bobrow, D. (1975). On data-limited and resource-limited processes. *Cogn. Psychol.* 7, 44–64.

Olivers, C. N., and Meeter, M. (2008). A boost and bounce theory of temporal attention. *Psychol. Rev.* 115, 836–863.

Pelli, D., Burns, C., Farell, B., and Moore-Page, D. (2006). Feature detection and letter identification. *Vision Res.* 46, 4646–4674.

Petit, J.-P., Midgley, K. J., Holcomb, P. J., and Grainger, J. (2006). On the time course of letter perception: a masked priming ERP investigation. *Psychon. Bull. Rev.* 13, 674–681.

Schacter, D., Cooper, L., and Delaney, S. (1990). Implicit memory for unfamiliar objects depends on access to structural descriptions. *J. Exp. Psychol. Gen.* 119, 5–24.

Teichner, W., and Krebs, M. (1974). Laws of visual choice reaction time. *Psychol. Rev.* 81, 75–98.

Theeuwes, J. (1991). Cross-dimensional perceptual selectivity. *Percept. Psychophys.* 50, 184–193.

Theeuwes, J., Van Der Burg, E., and Belopolsky, A. (2008). Detecting the presence of a singleton involves focal attention. *Psychon. Bull. Rev.* 15, 555–560.

Treisman, A., and Gelade, G. (1980). A feature-integration theory of attention. *Cogn. Psychol.* 12, 97–136.

Treisman, A., and Sato, S. (1990). Conjunction search revisited. *J. Exp. Psychol. Hum. Percept. Perform.* 16, 459–478.

Treisman, A. M. (1964). Verbal cues, language, and meaning in selective attention. *Am. J. Psychol.* 77, 206–219.

Tsal, Y., and Benoni, H. (2010). Diluting the burden of load: perceptual load effects are simply dilution effects. *J. Exp. Psychol. Hum. Percept. Perform.* 36, 1645–1656.

Turatto, M., Valsecchi, M., Seiffert, A. E., and Caramazza, A. (2010). On the speed of pop-out in feature search. *J. Exp. Psychol. Hum. Percept. Perform.* 36, 1145–1152.

Van Selst, M., and Jolicoeur, P. (1994). A solution to the effect of sample size on outlier elimination. *Q. J. Exp. Psychol.* 47A, 631–650.

Wolfe, J. (1994). Guided search 2.0: a revised model of visual search. *Psychon. Bull. Rev.* 1, 202–238.

Wolfe, J. M. (1992). "Effortless" texture segmentation and 'parallel' visual search are not the same thing. *Vision Res.* 32, 757–763.

Wolfe, J. M. (2007). "Guided search 4.0: current progress with a model of visual search," in *Integrated models of cognitive systems,* ed. W. Gray (New York, NY: Oxford), 99–119.

Yantis, S., and Johnston, J. C. (1990). On the locus of visual selection: evidence from focused attention tasks. *J. Exp. Psychol. Hum. Percept. Perform.* 16, 135–149.

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