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Opposite Effects of Capacity Load and Resolution Load on Distractor Processing

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Abstract

According to the load theory of attention, an increased perceptual load reduces distractor processing whereas an increased working memory load facilitates distractor processing. Here we raise the possibility that the critical distinction may instead be between an emphasis on resolution and an emphasis on capacity. That is, perceptual load manipulations typically emphasize resolution (fine-grained discriminations), whereas working memory load manipulations typically emphasize capacity (simultaneous processing of multiple relevant stimuli). To test the plausibility of this hypothesis, we used a visual working memory task that emphasized either the number of items to be stored (*capacity load*, retaining two versus four colors) or the precision of the representations (*resolution load*, detecting small versus large color changes). We found that an increased capacity load led to increased flanker interference (a measure of distractor processing), whereas an increased resolution load led to reduced flanker interference. These opposite effects of capacity load and resolution load on distractor processing mirror the previously described opposite effects of perceptual load and working memory load.

Attention can operate at early stages of processing to influence perception or at late stages of processing to influence working memory encoding and response selection (see review by Luck & Vecera, 2002). What determines the stage at which attention operates? To answer this question, Lavie and colleagues proposed the load theory of attention (Lavie, 1995, 2005; Lavie & Tsal, 1994). According to this theory, an increased perceptual load (e.g., detecting a target among multiple distractors versus one distractor) causes attention to operate at a relatively early stage of processing. This is because high perceptual load depletes perceptual processing capacity, thus leaving little room for irrelevant distractor. In contrast, increasing the working memory load interferes with top-down attentional control processes and thereby reduces the filtering of distractors, leading to increased interference (de Fockert, Rees, Frith, & Lavie, 2001; Lavie, Hirst, de Fockert, & Viding, 2004; Yi, Woodman, Widders, Marois, & Chun, 2004).

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However, it is difficult to be certain that the critical distinction is between perceptual load and working memory load per se, because the methods used to manipulate perceptual load and working memory load differ in multiple ways. In particular, perceptual load manipulations typically require high resolution processing so that observers can make fine-grained discriminations. For example, Lavie (1995, Experiment 3) manipulated perceptual load by comparing a letter detection task (which presumably required minimal precision) with a letter discrimination task (which presumably required much greater precision). Other experiments used manipulations that required either loose or tight binding of features to locations (e.g., Lavie, 1995, Experiment 2), which can be viewed as a manipulation of spatial resolution. Some previous studies in which the load manipulations could be construed as resolution manipulations are summarized in Table 1. In contrast, working memory load manipulations typically emphasize capacity (e.g., simultaneous processing or maintenance of multiple relevant stimuli, Lavie et al., 2004).

The present study used subtle variations within a single working memory task to test whether varying the need for resolution or capacity within working memory would lead to opposite effects on distractor processing, just like previous manipulations of perceptual versus memory load. We predicted that increasing the demand for working memory precision would lead to decreased distractor interference, just like previous manipulations of perceptual load, and that increasing the demand for working memory capacity would lead to increased distractor interference, just like previous manipulations of working memory load. This pattern would establish the plausibility of the idea that resolution versus capacity load is a relevant factor in determining distractor suppression, instead of (or in addition to) the factor of perceptual versus working memory load.

To compare low and high capacity loads, subjects were required to store either 2 or 4 colors in working memory to perform a change detection task (see Figure 1, Woodman, Vogel, & Luck, 2001); the need for precision was minimized by the use of a large change magnitude on change trials. To compare low and high resolution loads, set size was held constant at 2, and subjects were required to detect either large or small color changes. More precise memory representations are required to detect small changes than large changes (Awh, Barton, & Vogel, 2007). The Eriksen flanker task (Eriksen & Eriksen, 1974) was inserted into the retention interval of the change detection task (see Figure 1) so that we could measure distractibility. We predicted opposite effects of the two working memory loads on flanker interference: resolution-oriented working memory load should reduce interference from irrelevant distractors, whereas capacity-oriented working memory load should increase distractor interference.

Method

Participants

Eighteen observers between the ages of 18 and 30 with normal color vision and normal or corrected-to-normal visual acuity participated in this experiment for course credit. One participant used the wrong response buttons and was excluded from data analyses, leaving a total of 17 observers.

Stimuli

The experiment was run on a Mac Pro using MATLAB (The MathWorks, Cambridge, MA) and Psychtoolbox (Brainard, 1997). Stimuli were presented on a CRT monitor with a gray background (15.1 cd/m^2) and a continuously visible fixation point at a viewing distance of 57 cm.

For the change detection task (see Figure 1), the *sample array* consisted of 2 or 4 colored squares, each subtending 0.9° × 0.9° of visual angle. Their positions were randomly chosen from 4 locations centered ±2° and ±1° horizontally from fixation. The colors were quasi-randomly selected from a master set of 180 evenly distributed and isoluminant hues on a circle in the perceptually homogeneous CIELAB color space (for details, see Zhang & Luck, 2008), with the constraint of at least 48° in color space between any two colors in the sample array. The *test array* consisted of a single colored square (single probe) at the location of a randomly picked colored square in the sample array. This probe was either the same color as the corresponding color from the sample array ($p = .5$) or a different color ($p = .5$). When the color changed between sample and probe, the change magnitude was large (96° in color space) or small (24° in color space).

Three different variants of the change detection task were tested in different blocks so that we could separately vary the capacity load and the resolution load: set size 2 with large change magnitudes (baseline); set size 4 with large change magnitudes (high capacity load); and set size 2 with small change magnitudes (high resolution load). The change magnitude in the high resolution load condition was chosen, on the basis of pilot testing, so that overall memory accuracy in this condition would be similar to that in the high capacity load condition. Note that a full factorial design would have included a condition with a high capacity load and a high resolution load. However, pilot testing showed that memory performance was close to chance in this condition. In addition, the predicted effects of capacity load and resolution load on distractor processing would be expected to cancel each other out in this condition. Consequently, we did not include this condition in the final experimental design.

The stimulus and procedure for the flanker task were modeled after Lavie et al (2004). The target letter (0.41° × 0.62°) was equally likely to be presented at one of six possible positions along the horizontal meridian (centered ±2.5°, 1.5° and 0.5° from fixation). The target letter was equally likely to be a lowercase x or z. A distractor letter (0.67° × .90°) was presented 1.2° above or below the fixation point. The distractor letter was equally likely to be an uppercase X, Z, or N. This yielded three flanker compatibility conditions: compatible (x target and X distractor; z target and Z distractor), incompatible (x target and Z distractor; z target and X distractor), and neutral (either target and N distractor) (see Figure 1).

Procedure

Each trial began with an 800-ms fixation screen that was immediately followed by a 200-ms sample array. A 2000-ms blank screen followed the sample array to ensure enough time for working memory consolidation. The target and distractor for the flankers task then appeared on the screen for 2000 ms and were then replaced by central fixation for 500 ms. Observers reported whether the target letter was “x” or “z”, using two buttons, as quickly and accurately as possible within a time window of 2500 ms. Trials with no responses within this time window were treated as “misses” for the flanker task. Observers were explicitly instructed to ignore the distractor letter and respond only to the target. After this time, a memory probe appeared and remained present until a response was made. Observers reported whether the probe was the same color as the corresponding sample item using two gamepad buttons that were different from the response buttons for the flanker task. The two buttons for the flanker task and the two buttons for the memory task were located on the opposite sides of the gamepad (to minimize response interference between the two tasks). Accuracy rather than speed was stressed for the memory task, and the responses were not timed. A 500-ms computer generated beep was presented at the end of the trial if an error was made in either task or if no response was made in the flanker task.

Flanker target identities (x or z), flanker distractor positions (above or below fixation), flanker compatibility conditions (compatible, incompatible, and neutral), and change detection probe type (same or different color) were independently randomized within blocks. Thus, flanker stimuli were not predictive of change detection responses (same or different). The three working memory load conditions were blocked, but their order was counterbalanced across participants. Each participant completed 72 experimental trials preceded by 16 practice trials in each block. This yielded 24 trials for each combination of the three conditions of the flanker compatibility and the three conditions of working memory load.

Results

Flanker task

Figure 2a shows the reaction time (RT) data on trials with correct flanker task responses[1], and Figure 2b shows the compatibility effects (incompatible minus compatible difference scores). In general, the compatibility effects were increased in the high capacity load condition and decreased in the high resolution load condition relative to the low load baseline condition.

Correct RT (see Figure 2a) was subjected to a two-way within-subject analysis of variance (ANOVA) with factors of working memory load (low-load, high capacity load, high resolution load) and flanker compatibility (compatible, incompatible, neutral). The main effect of flanker compatibility on correct RT was significant [$F(2,32)=39.97$, $p<.001$, $\eta_p^2=.714$], reflecting the standard flanker RT effect with slower RTs on incompatible trials and faster RTs on compatible trials relative to neutral trials. The main effect of working memory load on correct RTs did not approach significance [$F<1$], but the interaction between

[1]Unlike Lavie et al. (2004), we did not exclude trials with incorrect change detection responses in the analyses of flanker RTs. Exclusion of those trials would lead to insufficient number of trials for the two high working memory load conditions. More importantly, incorrect change detection does not usually mean that the subject failed to devote full effort to the memory task. Instead, errors are typically a result noise in the memory representation (when the change magnitude is small) (Awh et al., 2007) or a failure to encode the tested item into working memory (when the set size is large). Therefore it is neither practical nor necessary to exclude incorrect change detection trials.

working memory load and distractor compatibility was significant [$F(4,64)=5.73$, $p=.001$, $\eta_p^2=.264$].

To highlight the opposite effects on the flanker task by the high-capacity load and high-resolution load, we computed incompatible-minus-compatible difference scores (see, Lavie et al., 2004), as shown in Figure 2b. Pairwise comparisons showed that the difference scores were significantly higher for the high-capacity load condition than for the low load condition [$F(1,16)=4.59$, $p=.048$, $\eta_p^2=.223$], but were significantly smaller for the high-resolution load condition compared to the low-load condition [$F(1,16)=4.55$, $p=.049$, $\eta_p^2=.221$].

A similar ANOVA conducted on the error rates (see Table 2) revealed a significant main effect of flanker distractor compatibility [$F(2,32)=22.62$, $p<.001$, $\eta_p^2=.586$], reflecting increased error rates on incompatible trials. Neither the main effect of working memory load [$F(2,32)<1$, $\eta_p^2=.005$] nor the interaction between working memory load and distractor compatibility [$F(4,64)=1.01$, $p=.410$, $\eta_p^2=.059$] reached significance. Error rates were near floor, however, making it difficult to determine whether they were impacted by the working memory load.

The overall magnitude of the flanker compatibility RT effect (126 ms, averaged across working memory load conditions) was larger than what is typical in the absence of a simultaneous working memory load (e.g., 10~40 ms, Lavie, 1995). However, this effect is similar to what has been reported previously in similar dual-task experiments (e.g., Lavie et al., 2004). This may be a result of the fact that all of our conditions involved some load on working memory capacity. Alternatively, it may reflect the executive control demands of performing two tasks simultaneously rather than working memory storage capacity demands per se (Lavie et al., 2004).

Change detection task

As shown in Table 3, change detection accuracy was substantially lower for the capacity load and resolution load conditions than for the baseline (low load) condition, leading to a significant main effect of load type [$F(2,32)=39.50$, $p<.001$, $\eta_p^2=.712$] in a two-way within-subject analyses ANOVA with factors of working memory and flanker compatibility. This confirms that the load manipulations were effective. Critically, however, a pairwise comparison yielded no significant difference between the high-capacity and high-resolution conditions [$F(1,16)=1.35$, $p=.263$, $\eta_p^2=.078$]. Therefore, the opposite effects on flanker compatibility RT by these two working memory loads cannot be attributed to differences in general task difficulty or arousal. In addition, neither the main effect of flanker compatibility [$F(2,32)=2.46$, $p=.101$, $\eta_p^2=.133$] nor the interaction between working memory load and distractor compatibility [$F(4,64)=1.36$, $p=.258$, $\eta_p^2=.078$] was significant.

Discussion

The present results demonstrate that flanker interference can be either increased or decreased by an increased working memory load depending on whether the load involves resolution or storage capacity. Increasing the capacity load led to increased flanker interference, as in previous studies (Lavie & De Fockert, 2005; Lavie et al., 2004), but increasing the resolution load led to decreased flanker interference. Thus, by making relatively subtle changes to a single working memory task, it is possible either to decrease or increase the amount of interference produced by a distractor. This is inconsistent with the idea that any kind of increased working memory load will lead to increased distractor interference, but it is consistent with several previous studies in which high demands for precision (e.g., working memory for faces) were accompanied by decreased distractor processing (Sreenivasan & Jha, 2007).

Moreover, because the effect of increasing the resolution load was in the same direction as previously observed effects of increased perceptual load, it is possible that the previous perceptual load effects were not a result of loading perception per se, but instead reflected an increased need for resolution in the high-load perceptual tasks relative to the low-load perceptual tasks. However, additional research will be needed to determine whether a single underlying resolution factor underlies both the present effects and the prior effects that were attributed to perceptual load. At a minimum, however, the present results demonstrate that the effect of a working memory load on distractor interference depends on whether resolution or capacity is emphasized by the memory task.

It is important to consider the possibility that our resolution load condition actually involved an increased perceptual load, which in turn yielded reduced flanker interference. This is very unlikely, however, because the perceptual portion of the working memory task preceded the flanker task by 2000 ms, whereas previous demonstrations of perceptual load effects involved manipulations of the stimuli that were present at the same time as the flanker stimuli. Moreover, it is not obvious that forming a precise representation of two colored squares would be more perceptually demanding than forming a coarse representation of four colored squares.

An alternative interpretation of the present findings is that the differences in distractor processing may result from different encoding strategies across the working memory load conditions. Specifically, it is conceivable that participants verbally encoded the colors in the sample array in the low load and high capacity load conditions, for which the color changes were always so large that they crossed typical color category boundaries. In the high resolution condition, however, the color changes were typically within a category, making verbal encoding an ineffective strategy. If participants engaged in verbal coding in the high capacity load condition but not in the high resolution load condition, this could potentially explain the different patterns of flanker interference observed in these two conditions.

Although this alternative account is possible, it is very unlikely. First, substantial effort is required to create a verbal code for more than a single item with a 200-ms sample array, so it is unlikely that the unpaid volunteers in the present study spent the effort to verbally encode the four items in the high capacity load condition. Second, the colors were randomly sampled from 180 different hues, many of which are difficult to name given that they fell between typical color categories. Finally, Luck & Vogel (1997) found that color change detection performance is not improved when participants have the opportunity to engage in verbal storage, so participants in the present study would have had no motivation to encode the stimuli verbally. Moreover, even if the verbal working memory load increased on high capacity load trials relative to low load trials, this is still consistent with our main conclusion that capacity and resolution loads have opposite effects on distractor processing. That is, increasing the capacity requirements (whether verbal or visual) led to increased interference, whereas increasing the resolution requirements led to decreased interference.

What, then, is the mechanism by which increasing the resolution load led to decreased interference? One possibility is that an increased resolution load focuses attention on finer spatial scales, which might also reduce flanker interference. In contrast, increased capacity load leads attention to be spread across coarser spatial scales (e.g., Ahmed & de Fockert, 2012), which increases flanker interference. A similar mechanism was previously proposed to underlie the modulation of the breath of attentional selection with negative and positive emotions (Rowe, Hirsh, & Anderson, 2007). Additional research is needed to verify this explanation of the reduced interference produced by a resolution load.

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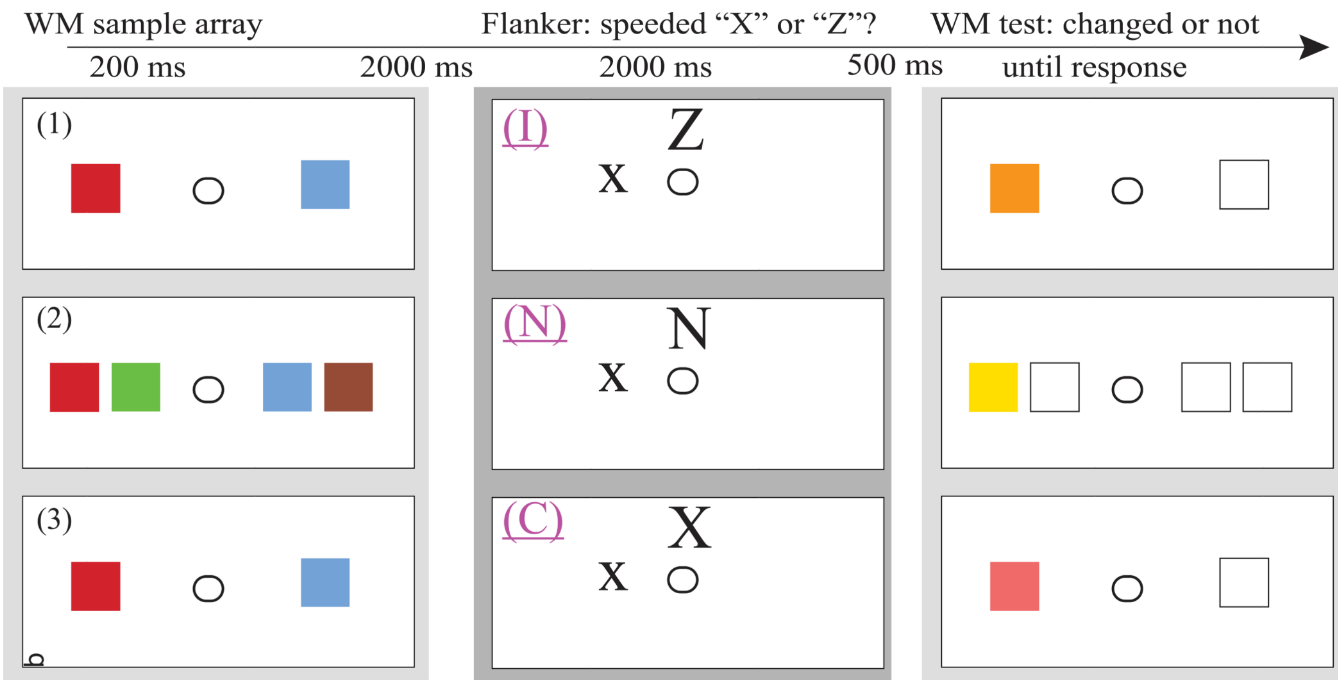

Figure 1.

Examples of stimuli and procedure. The flanker task was inserted during the retention interval of the color change detection task. The combinations of the flanker compatibility conditions [Incompatible (I), Neutral (N), and Compatible (C)] and working memory load conditions [low-load (1), high-capacity (2), and high-resolution (3)] were randomly mixed within blocks. Stimuli are not drawn to scale.

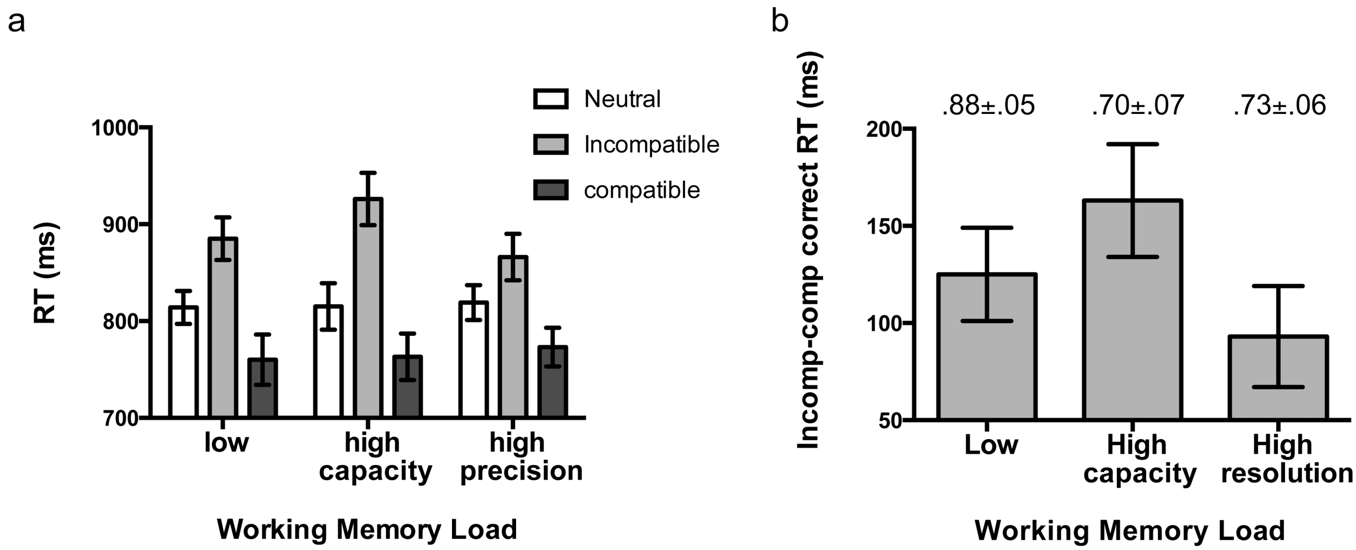

Figure 2.

RT results for the flanker task across three working memory load conditions. (a) Reaction time on trials with correct flanker task responses. (b) Flanker compatibility effects assessed as the difference in RT between incompatible and compatible trials. High-capacity and high-resolution conditions resulted in increased and reduced distractor interference, respectively, compared to the low-load condition. The digits above the bars are accuracy (mean ± within-subjects 95% confidence interval) for the change detection task, aggregated across flanker compatibility conditions. All error bars represent within-subjects 95% confidence intervals (Cousineau, 2005).

Table 1

Some previous load manipulations that could be construed as resolution manipulations

Studies	Tasks used for perceptual load manipulations		Relationship to precision requirements
	Low perceptual load	**High perceptual load**	
(Experiment 3 from Lavie, 1995)	Detection	Discrimination	Low precision may be sufficient for detection but not for discrimination
(Experiment 1 Handy, Soltani, & Mangun, 2001; Experiment 2 from Lavie, 1995)	Feature search	Conjunction search	Low spatial resolution may be sufficient for features but not for conjunctions
(Experiment 1 from Lavie, 1995)	Low display set size	High display set size	Set size was confounded with density, so higher spatial precision was needed for the higher set size
(Lavie & Cox, 1997; Macdonald & Lavie, 2008)	Easy (pop-out) search with homogeneous distractors	Hard visual search with heterogeneous distractors	Low precision may be sufficient for pop-out search but not for inefficient search
(Rees, Frith, & Lavie, 1997)	Was the target word in upper case?	Was it a bisyllabic word	Less precision needed for judging letter case than for reading a word
(Cartwright-Finch & Lavie, 2007)	Perceptual decision on categorical information (which of two lines was green)	Perceptual decision on metric information (which of two lines was longer)	Metric judgments typically require more precision than categorical judgments
(Experiment 2 from Handy et al., 2001)	A/H discrimination	A/H discrimination with shorter presentation time & backward masking	Sensory degradation incurs increased demands on precise coding

Table 2

Experiment 1. Mean Error Rates (mean± within-subject 95% confidence interval) on the Flanker Task as a Function of Working Memory Load

Working memory load	Flanker distractor compatibility			
	C	**I**	**I-C**	**N**
Low load	1±2	6±3	5±3	2±2
High capacity load	2±2	4±2	2±2	3±2
High resolution load	1±2	5±1	4±2	2±2

Table 3

Experiment 1. Accuracy (mean±within-subjects 95% confidence interval) on the Working Memory Task as a Function of Working Memory Load

Working memory load	Flanker distractor compatibility		
	C	I	N
Low load	90±4	89±5	87±6
High capacity load	71±6	72±7	67±6
High resolution load	70±6	76±5	73±6