Perceptual and cognitive load interact to control the spatial focus of attention

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Abstract

Caparos and Linnell (2009, 2010) used a variable-separation flanker paradigm to show that (i) when cognitive load is low, increasing perceptual load causes spatial attention to focus and (ii) when perceptual load is high, decreasing cognitive load and increasing cognitive resources causes spatial attention to focus. Here, we tested whether the effects of perceptual and cognitive load on spatial focus remain when, respectively, cognitive load is high and perceptual load is low. It was found that decreasing cognitive load only causes spatial attention to focus when perceptual load is high, namely, when the stimulus encourages this. Moreover, and contrary to the widely held assumption that perceptual load focuses attention automatically (Lavie et al., 2004), perceptual load exerts its focusing effect only with the engagement of cognitive resources when cognitive load is low. In sum, perceptual and cognitive mechanisms exert interacting effects and operate in concert to focus spatial attention.

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To ensure efficient functioning, the brain must exclude irrelevant, distracting information. Selective spatial attention is widely thought to reduce distractor interference at both perceptual and post-perceptual levels, respectively, by focusing perceptual resources on the attended location and by blocking at post-perceptual or cognitive levels distractors that survive perceptual selection (Lavie, Hirst, de Fockert & Viding, 2004; Macdonald & Lavie, 2008; cf Tsal & Benoni, 2010).

These two types of selection have been studied using manipulations of perceptual and cognitive (working-memory) load. Lavie et al. (2004) manipulated both perceptual and cognitive load and measured the impact on distractor interference using the flanker paradigm (Eriksen & Hoffman, 1972). They required participants to make a two-alternative forced-choice (2-AFC) response to a single central target flanked by response-compatible or response-incompatible distractors that occurred at a fixed separation from the target. They found that decreasing perceptual load caused distractor interference to increase while, independently (and additively) increasing cognitive load caused interference to increase.

The independence of the effects of perceptual and cognitive load has provided support for the view (1) that perceptual and not cognitive load impacts on perceptual selection – compatible with perceptual selection being driven automatically by the passive recruitment of limited capacity perceptual resources – and (2) that cognitive and not perceptual load impacts on post-perceptual selection – compatible with post-perceptual selection being driven top-down by the active deployment of cognitive resources (Lavie et al., 2004; Macdonald & Lavie, 2008). However, the flanker paradigm measures overall selection, and cannot – when applied only at a fixed target-distractor separation – isolate perceptual from post-perceptual selection.

Perceptual selection can be distinguished from post-perceptual selection by its inherently spatial nature. Accordingly, Caparos & Linnell (2009, 2010) isolated perceptual selection by adding a manipulation of target-distractor separation to the flanker paradigm, measuring the spatial profile of interference around the attended location and equating the focus of the latter with the focus of perceptual resources that determines perceptual selection. They showed that (1) the profile of interference is shaped like a ‘Mexican hat’ (where distractor interference first decreases with separation but then increases; Müller, Mollenhauer, Rosler, & Kleinschmidt, 2005), so that the extent of focus of perceptual resources can be derived from the ‘bottom’ or turning point of the function (Caparos & Linnell, 2009, 2010); (2) increasing perceptual load causes the profile spatially to focus, at least when cognitive load is low (Caparos & Linnell, 2009, 2010); and (3) increasing cognitive load causes the profile spatially to defocus, at least when perceptual load is high (Caparos & Linnell, 2010). Thus, in contrast to Macdonald and Lavie (2008), they showed that cognitive load – like perceptual load – affects perceptual selection and the focus of spatial attention.

Because perceptual and cognitive load were not manipulated independently in Caparos & Linnell (2010), it was not clear whether perceptual and cognitive load exert independent or interacting effects on perceptual selection. It could be that perceptual load exerts its focusing effects independently of cognitive load and thus automatically, as has widely been claimed (Lavie & Tsal, 1994); equally, it could be that cognitive load exerts its effects independently of perceptual load, so that cognitive resources could be deployed to produce an additional and
voluntary focusing effect, irrespective of the perceptual load of the task (see left of Figure 1). On the other hand, it might be that perceptual load exerts its focusing effect non-automatically and only with the involvement of cognitive resources; additionally, cognitive resources might not have a focusing effect except when the stimulus encourages this, that is, when the perceptual load is high (see right of Figure 1).

**Figure 1.** Independent versus interactive effects of perceptual and cognitive load on the spatial focus of attention.

In two experiments, the current study used a variable-separation flanker paradigm to resolve whether perceptual and cognitive load exert independent or interacting effects on the profile of distractor interference by manipulating perceptual and cognitive load fully independently of each other. Experiment 1 used a task-based manipulation of perceptual load while Experiment 2 used a stimulus-based one (data from three of the conditions from Experiment 1 have already been reported in Caparos & Linnell, 2009, 2010).

Distractor interference was indexed in two different ways. In Experiment 1, interference was indexed by comparing behaviour on ‘response-incompatible’ trials (in which targets and distractors mapped to opposite and incompatible responses) with behaviour on ‘absent-distractor’ trials (in which no distractor was presented and in which consequently there was no opportunity for distractor interference to arise; Caparos & Linnell, 2010). In Experiment 2, a more common measure of interference was derived by comparing behaviour on ‘response-incompatible’ trials with behaviour on ‘response-compatible’ trials (in which targets and distractors mapped to the same response).

**Experiment 1**

**Method**

**Design.** A mixed design was used in which the category of distractor (response-incompatible, response-neutral or absent) and target-distractor separation were manipulated
within participants, and perceptual and cognitive load (high or low) were manipulated across participants.

**Participants.** 138 participants (106 females; 15 left-handed; mean age 21 yr; age range 16 to 36 yr), with reported normal or corrected-to-normal vision, participated in the experiment in exchange for course credits. They were all naïve as to the aims of the study.

**Stimuli and procedure.** The stimuli and procedure were as described in Caparos and Linnell (2009; 2010). On each trial, participants performed two perceptual tasks. The primary perceptual task was a flanker task with varying target-distractor separations. The participant was required to identify (as quickly but as accurately as possible) a central target letter (‘E’ or ‘F’) using a 2-AFC response while ignoring a distractor letter (response-incompatible or response-neutral) that could be presented in the periphery. By extracting the extent of distractor interference as a function of target-distractor separation, the profile of perceptual resources and its focus could be determined.

The secondary perceptual task was used to manipulate perceptual load (with a task-based manipulation; Lavie, 1995). On each trial, in addition to identifying a target letter, participants had either to detect the presence of a (high or low) gap in the letter – in the low-perceptual-load condition – with a 2-AFC (‘present’ or ‘absent’) response, or to discriminate the position of this gap – in the high-perceptual-load condition – with a 2-AFC (‘high’ or ‘low’) response (see Caparos & Linnell, 2009).

In addition to the two perceptual tasks, participants performed a cognitive-load task which consisted in memorizing one or six numbers. Thus, before each block of twenty flanker trials, a vertical array of six numbers was presented for 2500 ms. The participants had to memorize either (1) the lowest number of the sequence (low-cognitive-load condition) or (2) the whole sequence of six numbers in the order of presentation (high-cognitive-load condition). After each block of twenty trials, participants were asked to type in the number(s) they had memorized (there was no time limit, but sequence knowledge was required in the high-cognitive-load condition).

The different conditions of perceptual and cognitive load were performed by different groups of participants. For each participant, the experiment was preceded by 80 practice trials and consisted of 480 trials, across which the different target-distractor compatibility and separation conditions were presented intermixed and in randomized order.

**Results**

We analyzed the speed and accuracy of forced-choice target-identification responses (‘E’ or ‘F’) in the flanker task. Percentages of target-identification errors were analysed but were found not to be affected by any factor (all \( p \) values > 0.100) and are not reported here. Response latencies were analysed only (1) for trials where target identity was correctly discriminated, (2) when they were longer than 200 ms and fell within three standard deviations of the overall mean for the participant and (3) when they occurred in trials where the presence/location of the gap on the secondary perceptual task was correctly identified/discriminated.

For each participant, mean target-identification RTs were calculated for incompatible-and neutral-distractor trials at each of the five target-distractor separations (1.8, 3.6, 5.4, 7.2 and 9.0 deg); moreover, for each participant, absent-distractor RTs were randomly separated
into five bins that were used to generate baseline data for the five different target-distractor separations (see Figure 2a). For each participant, interference as a function of separation was calculated by subtracting absent-distractor RTs from incompatible-distractor RTs at each target-distractor separation (see Figure 2b). Then, for each participant, the interference function of separation was fitted using a cubic model and the separation at which the ‘local minimum’ or bottom of the function occurred (i.e., the point where the function stopped decreasing and started increasing) was estimated by calculating the derivative of the fitted function (see Caparos & Linnell, 2009, 2010). The effects of perceptual and cognitive load on the location of the bottom of the function were tested using an independent-design two-way ANOVA.

![Figure 2. The figure shows (2a) incompatible-, neutral- an absent-distractor mean latencies (in ms) and (2b) distractor interference (incompatible- minus absent-distractor RTs; in ms) as a function of target-distractor separation (in deg), perceptual load (low or high) and cognitive load (low or high). Error bars depict +/- 0.5 SEM. (ID) = Incompatible distractor; (ND) = Neutral distractor; (AD) = Absent distractor; (FOA) = attended location.](image)

First, it was found that neither the main effect of Perceptual Load nor that of Cognitive Load was significant (respectively \( F(1,134) = 1.81, p = 0.181, \eta^2_p = 0.013 \) and \( F(1,134) = 1.39, p = 0.240, \eta^2_p = 0.010 \)). On the other hand, the interaction between Perceptual Load and

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1 Absent-distractor RTs were used as a baseline in preference to neutral-distractor RTs given that this provides a more sensitive measure of distractor interference (Caparos & Linnell, 2010).
Cognitive Load was significant ($F(1,134) = 6.17, \ p = 0.014, \ \eta^2_p = 0.149$). The origins of this interaction were investigated by testing the effect of Perceptual Load at each level of Cognitive Load and the effect of Cognitive Load at each level of Perceptual Load.

**Effect of Perceptual Load at each level of Cognitive Load.** When cognitive load was low, increasing perceptual load caused the bottom of the interference function of separation to move towards the attended location (from 6.59 deg to 5.15 deg with increasing perceptual load; $t(70) = 3.49, \ p = 0.001, \ d = 0.862$). On the other hand, when cognitive load was high, increasing perceptual load did not significantly move the bottom of the interference function of separation (the bottom occurred at 6.10 deg with low perceptual load and at 6.52 deg with high perceptual load; $t(64) = 0.83, \ p = 0.412, \ d = 0.190$).

**Effect of Cognitive Load at each level of Perceptual Load.** When perceptual load was low, increasing cognitive load did not significantly move the bottom of the interference function of separation (the bottom occurred at 6.59 deg with low cognitive load and at 6.10 deg with high cognitive load; $t(66) = 0.96, \ p = 0.343, \ d = 0.286$). On the other hand, when perceptual load was high, increasing cognitive load caused the bottom of the interference function of separation to move away from the attended location (from 5.15 deg to 6.52 deg with increasing cognitive load; $t(68) = 3.33, \ p = 0.001, \ d = 0.837$).

**Discussion**

The results of Experiment 1 showed that perceptual and cognitive load exert interacting rather than independent effects, using a task-based manipulation of perceptual load.

**Experiment 2**

Experiment 2 attempted to generalise this finding to the more common stimulus-based manipulation of perceptual load (in which the number of noise stimuli surrounding the target was manipulated; Lavie, 1995). In addition to this change, a more common measure of distractor interference was used; instead of comparing incompatible- with no-distractor performance, we compared incompatible- with compatible-distractor performance.

**Method**

**Design.** A mixed design was used in which the category of distractor (response-incompatible or response-compatible) and target-distractor separation were manipulated within participants, and perceptual and cognitive load (high or low) were manipulated across participants.

**Participants.** 172 participants (132 females; 21 left-handed; mean age 20 yr; age range 18 to 31 yr), with reported normal or corrected-to-normal vision, participated in exchange for course credits. They were all naïve as to the aims of the study.

**Stimuli and procedure.** The stimuli were presented in black on a white background. Each trial started with a central fixation cross, shown for 1000 ms, followed by the stimulus display for 220ms and then, again, by the fixation cross until a response was recorded. On each trial, the stimulus display contained a left-pointing (’<’) or right-pointing (’>’) target.
arrow (subtending 1.4° horizontally and 1.75° vertically) presented along the vertical midline and participants used a 2-AFC to indicate the direction of the target arrow. The target was flanked both left and right by a left- or right-pointing distractor arrow (subtending 1.6° horizontally and 1.95° vertically) that occurred on the horizontal midline of the screen at a distance of 3.6°, 5.6°, 7.6°, 9.6° or 11.6° from the vertical midline. On half the trials, the direction of the distractor arrows was the same as that of the target (response-compatible trials) whereas, on the other half of the trials, the direction of the distractor arrows was opposite to that of the target (response-incompatible trials).

The target occurred at fixation or at 2.4° vertically above or below it. Perceptual load was manipulated by presenting either two (low-perceptual-load condition) or three (high-perceptual-load condition) up- or down-pointing filler arrows (of the same size as the target) above and below the target along the vertical midline. Filler arrows could occupy any of the three target locations or an additional two locations above and below them (see Figure 3). One or two dot placeholder(s) (of diameter 0.4°) were presented in the location(s) not occupied by target and filler arrows.

**Figure 3.** Schematic illustration of a stimulus display from the high-perceptual-load condition. Here, the target arrow is pointing right and the distractors are response incompatible and separated by 5.6° from the vertical midline.

In addition to the flanker task, participants performed a cognitive-load task which consisted in memorizing one or six numbers. Each block of 8, 10 or 12 flanker trials was preceded by the presentation of one number (low-cognitive-load condition) or six numbers (high-cognitive-load condition) for 2500 ms. The participants had to memorize the number(s) presented and, after each block of trials, they had to type in the number(s) they had memorized (there was no time limit, but sequence knowledge was required in the high-cognitive-load condition).

The different conditions of perceptual and cognitive load were performed by different groups of participants. For each participant, the experiment was preceded by 30 practice trials.
and consisted of 600 trials, across which the different target-distractor compatibility and separation conditions were presented intermixed and in randomized order.

**Results**

We analyzed the speed and accuracy of forced-choice target-discrimination responses (“<” or “>”) in the flanker task. Percentages of target-discrimination errors were analysed but were found not to be affected by any factor (all p values > 0.100) and are not reported here. Response latencies were analysed in the same way as in Experiment 1 (see Figure 4a). The same analyses were also performed as in Experiment 1 except that incompatible-distractor RTs were compared to compatible-distractor RTs (instead of no-distractor RTs as in Experiment 1; see Figure 4b).

![Figure 4a. TARGET-DISCRIMINATION LATENCIES](image)

![Figure 4b. DISTRACTOR INTERFERENCE](image)

**Figure 4.** The figure shows (4a) incompatible- and compatible-distractor mean latencies (in ms) and (4b) distractor interference (incompatible- minus compatible-distractor RTs; in ms) as a function of target-distractor separation (in deg), perceptual load (low or high) and cognitive load (low or high). Error bars depict +/- 0.5 SEM. (ID) = Incompatible distractor; (CD) = Compatible distractor; (FOA) = attended location.

Again, it was found that neither the main effect of Perceptual Load nor that of Cognitive Load was significant (respectively, $F(1,168) = 3.25, p = 0.073, \eta^2_p = 0.019$, and $F(1,168) = 2.68, p = 0.104, \eta^2_p = 0.016$). On the other hand, the interaction between Perceptual Load and Cognitive Load was significant ($F(1,168) = 3.98, p = 0.047, \eta^2_p = 0.083$). The origins of this interaction were investigated by testing the effect of Perceptual
Load at each level of Cognitive Load and the effect of Cognitive Load at each level of Perceptual Load.

**Effect of Perceptual Load at each level of Cognitive Load.** When cognitive load was low, increasing perceptual load caused the bottom of the interference function of separation to move towards the attended location (from 8.44 deg to 6.90 deg with increasing perceptual load; \( t(83) = 2.58, p = 0.012, d = 0.511 \)). On the other hand, when cognitive load was high, increasing perceptual load did not significantly move the bottom of the interference function of separation (the bottom occurred at 8.30 deg with low perceptual load and at 8.37 deg with high perceptual load; \( t(85) = 0.14, p = 0.892, d = 0.070 \)).

**Effect of Cognitive Load at each level of Perceptual Load.** When perceptual load was low, increasing cognitive load did not significantly move the bottom of the interference function of separation (the bottom occurred at 8.44 deg with low cognitive load and at 8.30 deg with high cognitive load; \( t(92) = 0.26, p = 0.793, d = 0.074 \)). On the other hand, when perceptual load was high, increasing cognitive load caused the bottom of the interference function of separation to move away from the attended location (from 6.90 deg to 8.37 deg with increasing cognitive load; \( t(76) = 2.43, p = 0.018, d = 0.507 \)).

**Discussion**

The results of Experiment 2 confirmed that perceptual and cognitive load exert interacting rather than independent effects, using a stimulus-based manipulation of perceptual load.

**General Discussion**

The present study investigated whether perceptual and cognitive load exert interacting or independent (and additive) effects on perceptual selection. It indexed the effectiveness of perceptual selection using a variable-separation flanker paradigm to measure the spatial profile of perceptual resources and the extent of its focus (Caparos & Linnell, 2009, 2010).

It showed an interacting effect of perceptual and cognitive load on perceptual selection using both a task-based (Experiment 1) and a stimulus-based (Experiment 2) manipulation of perceptual load. Increasing perceptual load caused the spatial profile to focus when cognitive load was low (Caparos & Linnell, 2009, 2010) but not when it was high, compatible with the idea that perceptual load exerts its focusing effect only with the involvement of cognitive resources, hence non-automatically. In addition, decreasing cognitive load caused the spatial profile to focus when perceptual load was high (Caparos & Linnell, 2010) but not when it was low, compatible with the idea that cognitive resources can be deployed to focus perceptual resources only when the stimulus encourages this, that is, when perceptual load is high (Theeuwes, Kramer, & Belopolsky, 2004).

These findings that perceptual and cognitive load interact are not necessarily at odds with the independent effects reported by Lavie et al. (2004) since the current study might not have been measuring the same thing: for example, different separations may have been sampled and the relative contribution of perceptual and post-perceptual interference may have differed. However, while the findings of the current study can arguably be reconciled with those of Lavie et al. (2004), the conclusions remain at odds: perceptual load exerts its
focusing effect non-automatically and only with the engagement of cognitive resources (see right of Figure 1). Thus, whether perceptual selection is effective or not – in other words, whether selection occurs at ‘early’ perceptual or ‘late’ post-perceptual levels – is not independently determined by the availability of limited capacity perceptual resources. This finding is compatible with the notion of an exhaustible supply of perceptual resources as long as one recognises that these resources are not automatically deployed (Torralbo & Beck, 2008). As shown here, cognitive resources are involved in directing perceptual capacity to the target.

In conclusion, the current study suggests (1) that perceptual load exerts its attentional focusing effect non-automatically and only with the engagement of cognitive resources; and (2) that cognitive resources can be deployed to focus spatial attention only when the stimulus necessitates this, that is, when perceptual load is high.
References


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