The interacting effect of load and space on visual selective attention

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In the study of visual attention, two major determinants of our ability to ignore distracting information have been isolated, namely, (1) the spatial separation from the focus of attention and (2) perceptual load. This study manipulated both factors using a dual-task adaptation of the flanker paradigm (Eriksen & Hoffman, 1973). It showed that (1) although attention followed a gradient profile under low perceptual load it followed a Mexican-hat profile under high perceptual load, consistent with the idea that increasing load focuses spatial attention; and (2) increasing perceptual load did not improve overall selectivity: Though selectivity improved at near separations, it was impaired at far ones. Load and spatial separation exert interacting effects.

Keywords: Perceptual load; Selective attention; Visual attention; Visual perception.

To ensure efficient attentional selection of task-relevant information, distracting information must be ignored. Visual selection depends on two factors: The spatial separation between distractors and the target at the attended location, and the level of perceptual load involved in extracting target information. Next we introduce work that has focused on separation and load factors separately, before arguing that they should be investigated in concert.

Studies of the effect of separation have attempted to map the distribution or profile of spatial attention by measuring the “attentional fate” of distractors as a function of their separation from the attended location.

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It has been widely reported that they interfere (through response competition) to an extent that decreases with their separation from the attended location (e.g., Eriksen & St. James, 1986). Such findings have generated widespread support for a “gradient” model of the profile of spatial attention (e.g., Yantis & Johnston, 1990). Recent studies, however, have suggested that the profile of attention is more complex and follows a “Mexican-hat” function. For example, Müller, Mollenhauer, Rösler, and Kleinschmidt (2005) showed that distractors interfere more at 4.7° than 2.5° from the attended location. According to the Mexican-hat model, attention first decreases but then increases (before tailing off) with increasing separation. The bottom of the function (where attention stops decreasing and starts increasing) represents the area of best exclusion (Cutzu & Tsotos, 2003; Hopf et al., 2006; Mounts, 2000a, 2000b).

In parallel to and independent of the investigation of the effect of spatial separation on distractor interference, other work has focused on the effect of perceptual load (Kahneman & Chajczyk, 1983). Numerous recent studies have shown that increasing perceptual load, or the difficulty of the perceptual task, at the attended location causes a decrease in distractor interference; it is argued that more attention is allocated to the attended location when a perceptual task is harder, leaving less attention for the processing of distractors removed from the attended location and thus improving attentional selectivity (Handy & Mangun, 2000; Lavie, 1995).

Both the studies manipulating spatial separation and those manipulating perceptual load have provided key advances in our understanding of selection mechanisms. Remarkably, however, the joint manipulation of these factors has been mostly overlooked. This is all the more remarkable given that it is not unlikely that these factors interact. Indeed, several authors have suggested that increasing perceptual load focuses spatial attention (e.g., Lavie & Tsal, 1994) by committing resources to the attended location that would otherwise have been available outside this location. However, no study has as yet combined a fine-grained spatial sampling of the attentional profile with a strong perceptual-load manipulation in order to test this.

This study employed a paradigm that has been used in both spatial-separation and load studies, namely, Eriksen’s flanker paradigm (Eriksen & Hoffman, 1972, 1973). The perceptual-load manipulation was a task-based one rather than the more common stimulus-based one (Lavie, 1995). The latter involves changing the number of items (noise) around the target and varying the location of the target, neither of which are conducive to isolating the effect of target–distractor separation.

The participants performed two tasks, a flanker and a load-manipulation task. They had first (in the flanker task) to identify a central target letter, while ignoring a distractor letter occurring at different eccentricities, and then (in the load task) to either detect the presence of a gap in the target—in the
In each trial, a target letter ("E" or "F") occurred at the centre of the screen and a to-be-ignored distractor ("E", "F", or "X") occurred in the periphery at one of five target-distractor separations (1.8, 3.6, 5.4, 7.2, or 9.0°). Participants signalled (1) target identity and (2) in the low-perceptual-load condition, whether there was a gap in the target ("present" vs. "absent" 2-AFC), or, in the high-perceptual-load condition, where the gap was located ("high" vs. "low" 2-AFC). To view this figure in colour, please see the online issue of the Journal.

low-perceptual-load condition—or discriminate the position of this gap—in the high-perceptual-load condition (see Figures 1 and 2). The distractor (when it occurred) was always response-incompatible or response-neutral with the target. Comparing performance with incompatible and neutral distractors isolates the interference unique to incompatible distractors,

Figure 1. In each trial, a target letter ("E" or "F") occurred at the centre of the screen and a to-be-ignored distractor ("E", "F", or "X") occurred in the periphery at one of five target-distractor separations (1.8, 3.6, 5.4, 7.2, or 9.0°). Participants signalled (1) target identity and (2) in the low-perceptual-load condition, whether there was a gap in the target ("present" vs. "absent" 2-AFC), or, in the high-perceptual-load condition, where the gap was located ("high" vs. "low" 2-AFC). To view this figure in colour, please see the online issue of the Journal.

Figure 2. Target letter ("E") with a "low" and a "high" gap. To view this figure in colour, please see the online issue of the Journal.
namely response competition, which is thought to reflect the amount of attention allocated to the distractor location (Eriksen & Hoffman, 1972, 1973). With this new paradigm we can sample attention at the distractor location as a function of both its separation from the target (to reveal the profile of spatial attention) and the load exerted by the secondary task.

This study aimed at (1) replicating the Mexican-hat profile of spatial attention demonstrated by Müller et al. (2005) and (2) testing whether load focuses spatial attention (by shifting the location of the bottom of the Mexican-hat towards the attended location).

METHOD

Design and participants

Perceptual load was manipulated to be high or low in different groups of participants. The separation between target and distractor and the response compatibility of the distractor with the target (response-neutral or response-incompatible) were systematically manipulated within participants. Seventy-two participants from Goldsmith’ College (55 females; eight left-handed; mean age 20 years) took part in the experiment for course credits.

Stimuli and procedure

Stimuli were presented on a 17-inch monitor (operating at a refresh rate of 75 Hz) and were viewed from a distance of 60 cm. On each trial, the stimuli consisted of (1) an “E” or “F” target letter and (2) an “E”, “F”, or “X” distractor letter. The target letter (subtending 0.48 × 0.64”) was presented at the centre of the screen. In 90% of the trials, it had a small gap located either “high” or “low” in the upper half of its vertical axis. The distractor letter (subtending 1.60 × 1.90”) was presented along the horizontal midline of the screen, equally often on the left or right of the target and separated from it by either 1.8, 3.6, 5.4, 7.2, or 9.0” (the five levels of separation).

Distractors were response-incompatible with the target (e.g., it was “F” if the target was “E”) on 46% of trials. On the other 46% of trials, they were response-neutral (the letter “X”). In the remaining 8% of trials, no distractors were presented. We chose not to include response-compatible distractors in this study because (1) they provide an unreliable baseline (Lavie, 1995); (2) we have data (Caparos & Linnell, 2009) showing that the profile of attention is invariant with the presence/absence of compatible distractors (despite suggestions that the exclusion of compatible distractors produces facilitatory effect of incompatible distractors); and (3) we wished
to keep the experiment short (the interfering power of incompatible distractors decreases with practice).

Participants performed two tasks on each trial. The primary task was to discriminate, as quickly but as accurately as possible, the identity of the target (‘‘E’’ or ‘‘F’’) with a two-alternative forced-choice (2-AFC; using two fingers of the right hand). The secondary task was either to detect whether a gap was present in the target (‘‘present’’ vs. ‘‘absent’’ 2-AFC), in the low-perceptual-load condition, or to discriminate the position of the gap (‘‘high’’ vs. ‘‘low’’ 2-AFC), in the high-perceptual-load condition (using two fingers of the left hand). The two perceptual-load conditions were performed on identical stimuli. Feedback was given about incorrect responses for both tasks.

Each trial started with an empty screen for 700 ms, followed by the presentation of the stimuli for 100 ms. The experiment consisted of 480 trials, preceded by 80 practice trials. Conditions were presented intermixed and in randomized order, except for the two levels of perceptual load that were performed by different participants.

**RESULTS**

Before analysing target-identification performance on the primary task, we analysed results from the secondary task to ascertain that the perceptual-load task was adequately well performed. It was found that (1) in the gap-detection (low-perceptual-load) task, the gap was missed in 4.9% of ‘‘gap-present’’ trials and falsely reported in only 11.8% of ‘‘gap-absent’’ trials, and (2) in the gap-discrimination (high-perceptual-load) task, the gap was incorrectly reported as ‘‘high’’ in only 11.3% of ‘‘low-gap’’ trials and as ‘‘low’’ in 11.9% of ‘‘high-gap’’ trials.

Mean target-identification (‘‘E’’ or ‘‘F’’) RTs and errors were calculated for the two levels of load (only for gap-present trials on which the gap was correctly detected or discriminated) and for the five levels of target–distractor separation (1.8, 3.6, 5.4, 7.2, and 9.0\(^0\)) for incompatible-distractor and neutral-distractor trials (see Figure 3a for the RT data, which also shows mean no-distractor RTs; errors were all below 5\%). The effect of separation, perceptual load and distractor compatibility on target-identification RTs and errors was analysed by means of mixed-design ANOVAs and polynomial interpolations of the separation functions.

There were no main effects or interactions for the error data. The RT data, however, showed the usual effects: (1) RTs were faster with the low-perceptual-load (gap-detection) condition than with the high-perceptual-load (gap-position-discrimination) condition (551 vs. 595 ms, respectively), \(F(1,70) = 5.6, \text{MSE} = 61157.3, p = .021\), suggesting that the perceptual-
load manipulation was effective; (2) RTs were slower in incompatible- than neutral-distractor trials (578 vs. 568 ms, respectively), $F(1, 70) = 26.6$, $MSE = 717.7$, $p < .001$, showing that incompatible distractors created interference through response competition; (3) RTs varied with separation, $F(4, 280) = 12.9$, $MSE = 773.5$, $p < .001$; and (4) the interaction between separation and compatibility was significant, $F(4, 280) = 2.5$, $MSE = 778.9$, $p = .043$, showing that incompatible-distractor interference (as indexed by the difference between incompatible- and neutral-distractor RTs) varied with separation.

The novel findings were that: (1) The interaction between load and compatibility was not significant, $F(1, 70) = 0.047$, $MSE = 33.6$, $p = .83$, showing that there was no effect of load on incompatible-distractor interference; but (2) that there was a significant three-way interaction between separation, perceptual load, and distractor compatibility, $F(4, 280) = 3.7$, $MSE = 778.9$, $p = .006$. When this three-way interaction was broken down, there were significant interactions between separation and distractor compatibility in both low- and high-load conditions, $F(4, 140) = 3.0$, $MSE = 583.3$, $p = .02$, and $F(4, 140) = 3.2$, $MSE = 574.5$, $p = .016$, respectively, although subsequent trend analyses showed that the incompatible-distractor interference function of separation was best explained by a linear trend for the low-perceptual-load condition, $F(1, 35) = 9.9$, $MSE = 674.3$, $p = .003$ (other trends had $p$-values $>.4$), and a combination of quadratic and cubic trends for the high-perceptual-load condition, $F(1, 35) = 5.75$, $MSE = 681.6$, $p = .022$, and $F(1, 35) = 7.7$, $MSE = 435.0$, $p = .009$, respectively (the linear and quartic trends had $p$-values $>.8$) (see Figure 3b). This difference between the incompatible-distractor interference functions of separation in the two load conditions resulted in no overall effect of load across separation.

Next, polynomial interpolations were applied to the incompatible-distractor interference functions of separation, separately for each participant and perceptual-load condition. A cubic model was used on the assumption that the underlying profile of attention is shaped like a Mexican hat. (If the underlying profile is actually linear, the fitted function obtained with a cubic model will closely mirror that obtained with a linear model, because the quadratic and cubic coefficients will approach zero.) For each load condition, the separation at which the bottom of each function occurred was calculated by taking its derivative. When the bottom occurred outside the boundaries of the sampled interval, or when there was no derivative in the domain of real numbers, the local minimum was defined as the lowest point of the function within the sampled interval (1.8° or 9.0°). Across participants, the bottom occurred at 4.4° ($SEM = 0.28$) in the high-perceptual-load condition compared to 5.5° ($SEM = 0.42$) in the low-perceptual-load condition. This difference was significant, $t(70) = 4.2$,
Figure 3. (a) Absolute target-identification latencies shown as a function of distractor compatibility, target-distractor separation, and perceptual load. Error bars depict +/- 0.5 SEM. (▲) = low perceptual load with incompatible distractor; (●) = low perceptual load with neutral distractor; (○) = low perceptual load with no distractor; (◆) = high perceptual load with incompatible distractor; (■) = high perceptual load with neutral distractor; (□) = high perceptual load with no distractor; FOA = focus of attention; D = distractor-present trials; ND = no-distractor trials. (b) Incompatible-distractor interference (obtained by subtracting neutral-distractor from incompatible-distractor target-identification latencies) shown as a function of target-distractor separation and perceptual load. Error bars depict +/- 0.5 SEM. (▲) = low perceptual load; (◆) = high perceptual load; FOA = focus of attention.
It is noteworthy that, in the low-perceptual-load condition, the bottom of the interference function was estimated to occur at 5.5° with polynomial interpolations on individual data, whereas, from Figure 3, it would appear to have occurred at or above 9.0°. This discrepancy arises because Figure 3 displays the average of individual functions. The majority of these functions were actually shaped like Mexican hats, but they differed in their foci, causing them to average out as a gradient function with a bottom defined as the largest sampled separation (it is possible that some gradient profiles reported in the literature are an artefact of this averaging process).

**GENERAL DISCUSSION**

The first novel finding of this study was that the profile of attention around a central target is shaped like a Mexican hat under certain conditions: The interference from peripheral and unscaled incompatible distractors was shown first to decrease but then to increase with increasing separation (in the face of decreasing cortical magnification) in the high-perceptual-load condition (note that the distractors were not scaled for cortical magnification to avoid the possibility that the increase in interference with increasing separation was an artefact of overscaling). This finding constitutes an important generalisation of previous reports of Mexican-hat profiles around peripheral targets (e.g., Müller et al., 2005). Using central target presentation is arguably a more ecologically valid scenario since sustained covert attention to peripheral locations with fixed eyes is an exception rather than the rule: In everyday life, our eyes closely follow our attention.

In contrast to the Mexican-hat profile obtained when perceptual load was high, the more frequently reported gradient profile was found when perceptual load was low. It is unlikely that the profile of attention changes qualitatively with load, describing a Mexican-hat function when perceptual load is high but a gradient function when it is low. The more parsimonious interpretation of the data is rather that the profile of spatial attention is always shaped like a Mexican-hat function (indeed, individual data do describe Mexican-hat profiles at low, as well as high, load) but that different load conditions cause spatial attention to be more or less focused. Consistent with this idea, in a new study with peripheral stimulus presentation (Caparos & Linnell, 2009) we have replicated the Mexican-hat profile (as in Müller et al., 2005) under both low- and high-perceptual-load conditions, with the bottom of the function occurring closer to the attended location in the high-load condition. Because the present study used central rather than peripheral target presentation, perceptual load was inevitably lower overall and attention
more spread. This would have affected our manipulation of perceptual load so that in the low-perceptual-load condition spatial attention was too spread for the increasing arm of the Mexican-hat function to be sampled, especially against the effect of cortical magnification.

Differences in the perceptual load employed in past studies may thus explain why some have reported gradient profiles and others Mexican-hat ones. Although it is not feasible precisely to evaluate and compare perceptual loads across published studies, reports of gradient profiles may have involved low-perceptual-load settings, where the target always occurred at the expected location and/or the display was uncrowded (e.g., Henderson & Macquistan, 1993). Equally, reports of Mexican-hat profiles may have involved difficult perceptual tasks, where the target location was unknown and/or the display was crowded (e.g., Cutzu & Tsotsos, 2003).

Just as studies of the attentional profile (as a function of separation) need to study the profile at different loads, so too do perceptual-load studies need to examine effects of load at different separations from across the profile of spatial attention. Indeed, in this study, an increase in perceptual load caused no main effect across separation; the effect of load reversed between near and far separations (see Figure 3b). This finding is currently not predicted by the widely cited perceptual-load model (e.g., Lavie, 1995), according to which increases in perceptual load always cause a decrease in distractor interference. If separation is not considered in load studies, between-study comparisons and generalisations may be compromised, since the effect of perceptual load depends on separation.

In summary, this new adaptation of the flanker paradigm combined perceptual-load and target–distractor-separation manipulations and showed that the effects of perceptual load and separation interact. This has the following important implications. First, studies of the attentional profile should consider load. Our data are consistent with an effect of load on the spread of attention, which could explain why some researchers have reported a Mexican-hat profile of attention whereas others have reported a gradient. Second, studies of load should consider the profile of attention and not ignore spatial factors. Increasing perceptual load can impair selectivity at some spatial separations at the same time as improving it at others: Perceptual load does not improve overall selectivity.

REFERENCES

Caparos, S., & Linnell, K. J. (2009). The spatial focus of attention is controlled at perceptual and cognitive levels. Manuscript submitted for publication.


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