

The fate of task-irrelevant visual motion: Perceptual load versus feature-based attention

Shuichiro Taya

School of Psychology, University of Southampton,
Southampton, UK



Wendy J. Adams

School of Psychology, University of Southampton,
Southampton, UK



Erich W. Graf

School of Psychology, University of Southampton,
Southampton, UK



Nilli Lavie

Institute of Cognitive Neuroscience,
University College London, London, UK, &
Department of Psychology, University College London,
London, UK



We tested contrasting predictions derived from perceptual load theory and from recent feature-based selection accounts. Observers viewed moving, colored stimuli and performed low or high load tasks associated with one stimulus feature, either color or motion. The resultant motion aftereffect (MAE) was used to evaluate attentional allocation. We found that task-irrelevant visual features received less attention than co-localized task-relevant features of the same objects. Moreover, when color and motion features were co-localized yet perceived to belong to two distinct surfaces, feature-based selection was further increased at the expense of object-based co-selection. Load theory predicts that the MAE for task-irrelevant motion would be reduced with a higher load color task. However, this was not seen for co-localized features; perceptual load only modulated the MAE for task-irrelevant motion when this was spatially separated from the attended color location. Our results suggest that perceptual load effects are mediated by spatial selection and do not generalize to the feature domain. Feature-based selection operates to suppress processing of task-irrelevant, co-localized features, irrespective of perceptual load.

Keywords: perceptual load, feature-based attention, space-based attention, object-based attention, motion aftereffects

Citation: Taya, S., Adams, W. J., Graf, E. W., & Lavie, N. (2009). The fate of task-irrelevant visual motion: Perceptual load versus feature-based attention. *Journal of Vision*, 9(12):12, 1–10, <http://journalofvision.org/9/12/12/>, doi:10.1167/9.12.12.

Introduction

Attention enables us to select relevant information from a visual scene while disregarding irrelevant information to achieve particular behavioral goals. It has been well established that attending to a particular location can improve psychophysical performance and increase neural responses to stimuli at that location (e.g., Posner, 1980; Yantis et al., 2002). However, there has been some controversy regarding the fate of unattended visual information; specifically, whether it can be excluded from perceptual processing (Kahneman & Treisman, 1984; Lavie & Tsal, 1994 for review).

Load theory of attention (Lavie, 1995, 2005) suggests that this controversy can be resolved by considering the role of perceptual load in distractor processing. Under this theory the extent to which irrelevant stimuli are perceived depends on the level of perceptual load required by the

prevailing task. Tasks with high perceptual load will exhaust attentional resources by processing the task-relevant stimuli, leaving little or no capacity for other, task-irrelevant stimuli. In contrast, low perceptual load tasks leave spare capacity, which involuntarily ‘spills over’ to process irrelevant stimuli. These effects of perceptual load have been demonstrated for unattended stimuli at locations spatially separated from the task-relevant target (e.g., Lavie, 2005; Lavie & Cox, 1997; Lavie & Fox, 2000; Lavie, Ro, & Russell, 2003; Macdonald & Lavie, 2008 for review), but not for target and distractor stimuli presented at the same location (Chen, 2003) suggesting that load effects may be mediated by spatial selection (Handy & Mangun, 2000).

Although some theories suggest that attentional effects are always mediated by spatial selection (so that even color selection is mediated by attending to the locations of the attended color e.g., Tsal & Lavie, 1988, 1993) recent research has demonstrated more pure forms of

feature-based selection. These demonstrations typically show facilitated processing of an attended feature that extends across spatial locations (Liu, Larsson, & Carrasco, 2007; Liu, Stevens, & Carrasco, 2007; Maunsell & Treue, 2006; Sàenz, Buracas, & Boynton, 2002, 2003; Serences & Boynton, 2007; Treue & Martínez-Trujillo, 1999). For example, using both psychophysics and fMRI, Sàenz et al. (2002, 2003) showed that when observers attended to upward motion in one visual hemi-field, discrimination of upward motion improved not only in the attended visual hemi-field but also in the unattended visual hemi-field.

What are the processing consequences for an unselected/task-irrelevant feature? If load theory can be applied to feature-based selection, then this would depend on the level of load required to process the task-relevant feature; if load is high, processing of task irrelevant features will be considerably reduced. However, if load is low, task irrelevant features will also be automatically processed. On the other hand, a strong account of feature-based selection might predict reduced processing of an irrelevant feature (e.g., motion in a color based task) irrespective of the level of load required for the attended feature.

We tested these contrasting predictions by varying the level of perceptual load for a task based on one feature (color) and assessing the effects on the processing of an irrelevant feature (motion). Motion processing was assessed with the motion aftereffect (MAE). MAE results in an illusory sense of motion in one direction (say leftward) after a prolonged period of viewing motion in the opposite direction (rightward). MAEs can be modulated by spatial attention as Chaudhuri (1990) and others have shown (Alais & Blake, 1999; Blaser & Shepard, 2009; Rees, Frith, & Lavie, 1997; Rezac, Krekelberg, & Dobkins, 2004). In our first experiment we ask whether varying perceptual load for tasks related to either stimulus color or motion can modulate resultant MAEs when both task-relevant and irrelevant features belong to the same object, and are co-localized.

General methods

Stimuli

Stimuli were generated using the Psychophysics Toolbox for MATLAB (Mathworks; Brainard, 1997; Pelli, 1997) and presented on a 21-in CRT monitor (Iiyama, Vision Master 500) with a pixel resolution of 1152×864 and a refresh ratio of 85 Hz. Participants observed the stimuli at a 64 cm viewing distance in a dark room. Head motion was restricted by a chin-and-forehead rest.

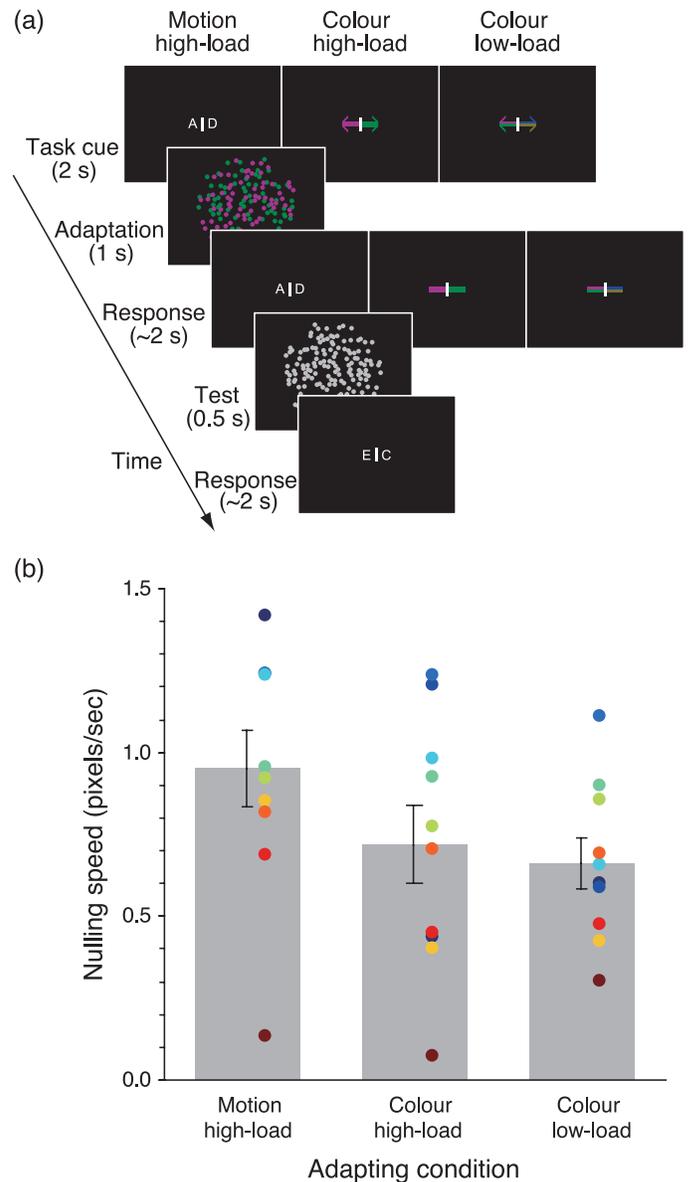


Figure 1. (a) Basic trial structure of all experiments (the specific task cues and stimuli presented here correspond to Experiment 1). (b) The resultant MAEs for Experiment 1 as defined by the speed required to null the illusory motion. The gray columns show the thresholds averaged across observer, collapsed across motion, acceleration and staircase directions ($N = 10$). Error bars represent ± 1 SE across observers. The colored dots indicate MAEs for individual observers.

The adaptation stimulus consisted either of red and green dots, or blue and yellow dots, while the test stimulus consisted solely of gray dots (Figure 1a). The percentage of the two dot colors in the adaptation stimulus was 53:47; red (blue) dots were more frequent than green (yellow) dots in half of the trials, and vice versa for the other trials. The four colors were calibrated to isoluminance for each

participant with a minimum-motion technique similar to that proposed by Anstis and Cavanagh (1983).

Procedure

Each trial included an adaptation phase and a subsequent test phase (Figure 1a). MAE was quantified by a nulling technique; for each condition we determined the test velocity that was perceptually stationary, using the QUEST adaptive staircase method (Watson & Pelli, 1983). In separate blocks, observers performed one of three, two-alternative forced choice (2AFC) tasks during the adaptation phase: (1) low-load color task: participants determined whether the adaptation stimulus was a mixture of red and green dots, or blue and yellow dots, (2) high-load color task: participants determined which of the two colors was more prevalent in the adaptation stimulus, (3) high-load motion task (Experiments 1 and 2 only): participants decided whether the moving dots were accelerating or decelerating.

Each trial started with a 2-sec presentation of a static task cue (see Figure 1a), followed by the adaptation stimulus (1 sec). The speed of the adapting dots increased or decreased linearly over the 1-sec presentation but always had an average speed of 1.3 deg/sec. Dots were anti-aliased (as implemented by the Psychophysics Toolbox) to produce sub-pixel accuracy. The speed increment (or decrement) was pre-determined for each participant to match the difficulty of the high-load motion task to the high-load color task (see Preliminary experiments section below). Observers responded, via a key press, after the offset of the adaptation stimulus, according to the task for the current block.

Two seconds after the offset of the adaptation stimulus, the MAE test stimulus appeared for 0.5-secs. The speed of the test dots varied from trial-to-trial in accordance with a QUEST staircase. Participants made a 2AFC decision about whether the dots were expanding or contracting. This task was intentionally different from the tasks during the adaptation phase, with the goal of manipulating feature-based attention while avoiding priming in the case of attention to motion. If an observer did not respond within 2-secs of the test offset, a beep was given and the entire trial was repeated. The next trial began 2-secs after the test offset.

Preliminary experiments

To ensure that the difficulty of the high-load color task was equivalent to that of the high-load motion task, we calibrated the increment (or decrement) of the speed of the adapting dots via two preliminary experiments. The adaptation stimulus (without the test phase) was presented with the same time course as the main experiment. Firstly, we determined performance (percent correct) for the high- and low-load color tasks. Secondly, participants performed the high-load motion task. Using QUEST, we

determined the speed change such that performance for the motion task matched that obtained for the high-load color task.

Experiment 1

We used two color tasks with different task demands (high-load and low-load) during adaptation. If load theory (Lavie, 1995, 2005) can be extended to the feature domain, then a high-load color task would consume full attentional capacity and motion processing would be reduced. Such a scenario would predict larger MAEs in the low-load color task than the high-load color task. We also included a high-load motion task to explore the effects of feature-based attention.

Methods

Moving dot patterns were presented within a 1.5 deg radius circular aperture. Each aperture contained 180 dots, which were expanding or contracting with 100% coherence. Dots subtended 0.09 deg and were presented against a black background. A small white fixation cross was visible at the center of the screen during stimulus presentation. The small stimulus diameter and central fixation made it unlikely that an OKN response would occur, as these movements are maximally produced by full-field motion. If observers did make eye movements, despite the instruction to fixate, this would add a translation component to the retinal motion without affecting the amount of expanding/contracting motion. These factors make it unlikely that eye movements affected the measured MAEs.

Ten observers including three authors (EWG, ST and WJA) took part in the experiment. All participants gave written informed consent, and the University of Southampton ethics committee approved the study. Twenty-four QUEST staircases (3 tasks \times 2 motion directions \times 2 accelerations \times 2 staircase directions; 16 trials each) were run in random order across 12 blocks. In half of the blocks participants adapted to expanding motion and in the other blocks they adapted to contracting motion. To prevent motion aftereffects from continuing across blocks, subjects viewed a static dot pattern for a minimum of 30-secs between blocks.

Results and discussion

Task performance

The average proportion correct across subjects for the motion task, the high-load color task, and the low-load color task were 0.67, 0.66, and 0.99, respectively. A nonparametric Friedman test showed a significant effect of

task difficulty ($\chi^2_{(2)} = 15.2, p < .05$) with higher accuracy in the low-load color task than either of the high-load tasks (Wilcoxon signed ranks test with Bonferroni correction: low-color vs. high-motion, $Z = 2.8, p < .05$; low-color vs. high-color, $Z = 2.8, p < .05$). There was no difference in accuracy between the high-load motion task and the high-load color task ($p > .1$), indicating that the two tasks were effectively matched for difficulty.

MAE

Figure 1b shows the strength of the MAE as a function of adaptation task. It can be seen that larger MAEs were obtained when observers attended to stimulus motion than when they attended to stimulus color. This is confirmed by a main effect of task (one way ANOVA: $F_{2, 9} = 5.6, p < .05$, the data for this and all subsequent ANOVAs did not deviate significantly from a normal distribution, Shapiro–Wilk test; all $p > .1$) with significantly larger MAEs in the high-load motion condition than the other conditions ($p \leq .05$; Tukey’s HSD test). In other words, motion processing was selectively facilitated under conditions where attention was directed to motion, even though motion and color belonged to the same object. However, there was no difference in MAE between the low-load and high-load color conditions. These results are consistent with predictions from feature-based selection but inconsistent with predictions derived from extension of load theory to feature-based selection.

These data suggest that processing capacity does not involuntarily spread to task-irrelevant features in the way that would be expected by load theory as extended to the feature domain. However, in our first experiment, the two features, color and motion, belonged to the same objects. Thus, it is possible that perceptual load effects were absent because some automatic co-selection of the non-relevant feature occurred due to object-based selection. A number of studies suggest that directing attention to a particular feature of an object will result in automatic co-selection of other features of that object (Blaser, Papathomas, & Vidnyánszky, 2005; Blaser, Pylyshyn, & Holcombe, 2000; Melcher, Papathomas, & Vidnyánszky, 2005; O’Craven, Downing, & Kanwisher, 1999; Rodríguez, Valdés-Sosa, & Freiwald, 2002; Sohn, Chong, & Papathomas, 2005; Sohn, Papathomas, Blaser, & Vidnyánszky, 2004). For example, Melcher et al. (2005) showed that when observers attend to a red stimulus, if that stimulus also happens to be moving upward, then processing of upward motion is facilitated across the visual field. Such feature co-selection suggests that the units of attentional selection are objects, at which spatio-temporally colocalized features are bound together automatically (e.g., Duncan, 1984; Egly, Driver, & Rafal, 1994; O’Craven et al., 1999). Although it is clear from our results that full co-selection did not occur; MAEs were stronger for the high-load

motion than the high-load color task, it is possible that partial co-selection of features prohibited or masked any load effects.

In our next experiment, we used a stimulus in which the color and motion belonged to distinct objects but still occupied the same spatial location. We hypothesized that such a stimulus might reduce the co-selection of features. We repeated our load manipulation to investigate whether, as the two features became perceptually more separable, we might see greater processing ‘spill-over’ across features under low-load, as predicted by load theory.

Experiment 2

Observers performed easy or hard color or motion tasks with two types of moving, colored stimuli (see Figure 2, and Methods below). In the first stimulus condition, small portions of a static, colored, patterned background were visible through an expanding pattern of circular apertures. We call this the ‘disco’ stimulus, because it simulates spotlights moving over a colored surface, like the reflections of a mirrored discoball on a colorful dance floor. In a second stimulus condition, as a control, we used ‘attached’ stimuli, in which segments of the colored pattern were attached to moving disks.

In the disco stimulus the color and motion were perceptually attributed to distinct objects while in the attached stimulus these two features belonged to the same objects. Using these stimuli we can ask two questions: Firstly, can higher-level surface segregation cues affect the level of object-based vs. feature-based attention? Secondly, if increased separation of feature processing occurs in our ‘disco’ condition, will this also facilitate load effects that were absent in Experiment 1?

Methods

Both types of adaptation stimuli, ‘disco’ and ‘attached,’ consisted of 100 moving disks presented within a 5.5 deg radius aperture. On any given frame, the two stimulus types had the same configuration and color and could not be differentiated (Figure 2a). However, motion information across successive frames produced clear perceptual differences, as confirmed by observers’ subjective reports.

The ‘disco’ stimulus (Figure 2b) consisted of back and frontal surfaces. The back surface had ‘dart-board’ like pattern, painted with isoluminant red and green, or blue and yellow in the proportion of 53:47. The frontal surface was uniformly black and opaque except for moving circular windows or apertures (0.4° diameter), through which small portions of the back surface were visible. All windows moved coherently in an expanding or contracting

pattern. The observer’s percept was of spotlights or apertures moving over a static, colored surface. The average speed of the moving apertures over each trial was 2.6 deg/sec but increased (or decreased) continuously. The increment or decrement ratio was pre-determined for each observer, as in [Experiment 1](#), such that difficulty was matched across high-load color and motion tasks.

In the ‘attached’ stimulus ([Figure 2c](#)), randomly selected segments of the dart-board pattern were attached to each disk, or aperture. As a result, with this stimulus,

observers perceived moving disks or spheres with fixed colored patterns. Other details were the same as for the ‘disco’ stimulus.

Twelve observers including three authors (EWG, ST, and WJA) participated. The strength of MAE was again measured via QUEST. Forty-eight staircases (2 stimulus types × 3 tasks × 2 motion directions × 2 accelerations × 2 staircase directions; 16 trials each) were run in random order across 6 blocks. All other details of the experiment were identical to [Experiment 1](#).

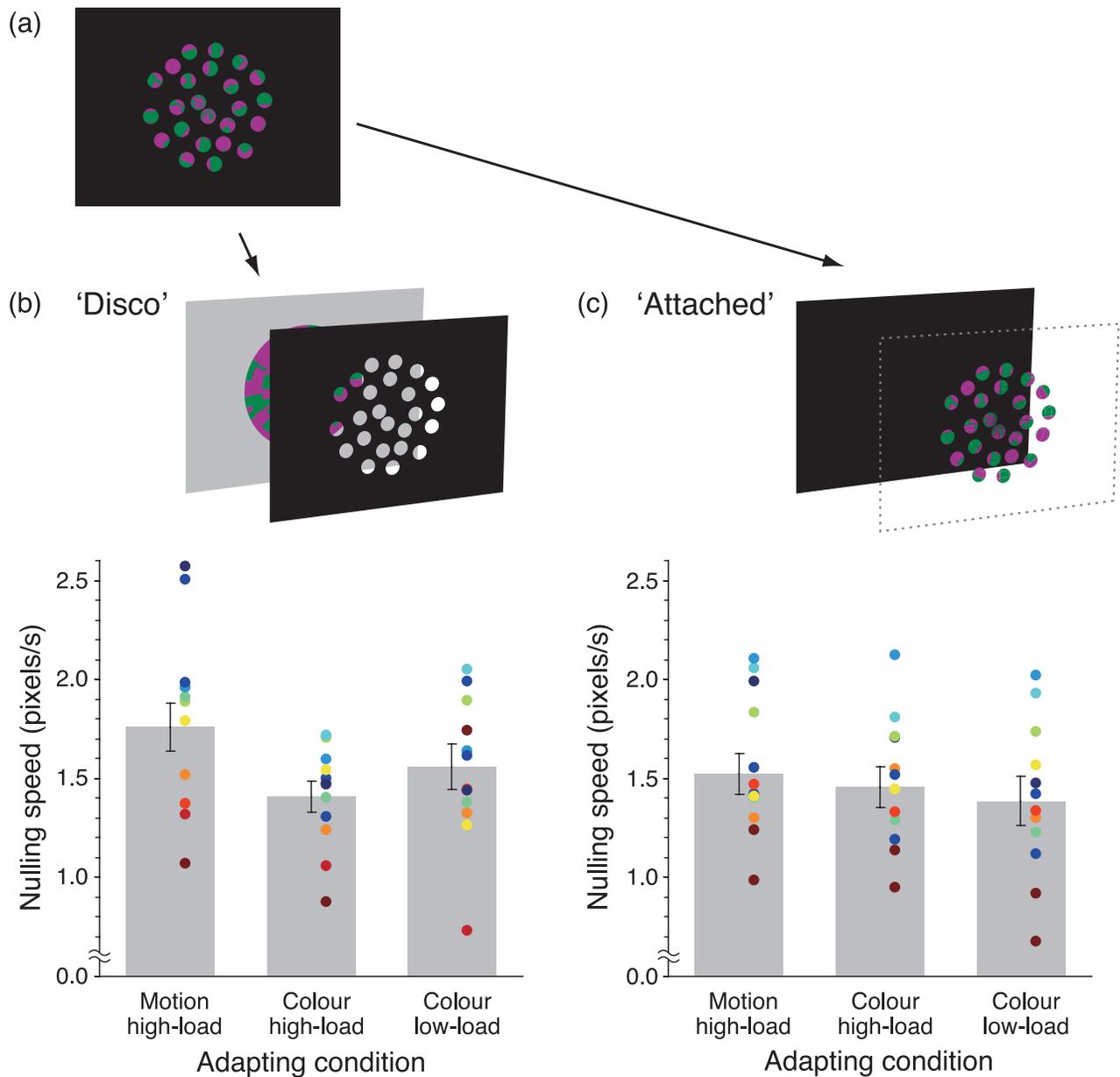


Figure 2. Stimuli and results for [Experiment 2](#). (a) Example of one stimulus frame of adapting stimuli. (b) ‘Disco’ condition: top figure shows schematic representation of adapting stimulus; the bottom panel shows the resultant MAEs averaged over 12 observers (gray columns) and for individuals (colored dots). (c) ‘Attached’ condition: top figure shows schematic representation of adapting stimulus; the bottom panel shows the resultant MAEs averaged over 12 observers (gray columns) and for individual observers (colored dots).

Results and discussion

Task performance

Task performance data confirm that our load manipulations were successful and well-matched across stimulus types. Accuracy rates for the high-load motion, low-load color, and high-load color tasks were 0.72, 0.99 and 0.71 for the disco stimuli and 0.67, 0.99 and 0.68 for the attached stimuli. There was a significant difference in accuracy across the six (2 stimulus type \times 3 conditions) tasks (Friedman test: $\chi^2_{(5)} = 42.6$, $p < .001$). Post-hoc tests (Wilcoxon signed ranks test, with Bonferroni correction) showed that, for both stimulus types, the low-load color task was easier than both high-load tasks (disco: low-color vs. high-motion, $Z = 3.1$, $p < .05$; low-color vs. high-color, $Z = 3.1$, $p < .05$; attached: low-color vs. high-motion, $Z = 3.1$, $p < .05$; low-color vs. high-color, $Z = 3.1$, $p < .05$), but there was no difference in difficulty between the two high-load tasks ($p > .1$). As expected, the stimulus type had no effect on accuracy across the three task conditions ($p > .1$).

MAE

Averaged MAEs are shown in [Figures 2b](#) and [2c](#). Similarly to [Experiment 1](#), we found a main effect of attended feature; larger MAEs were produced when attending to motion than when attending to color ($F_{1, 11} = 16.56$, $p < .005$). As expected, there was no main effect of stimulus type ('disco' vs. 'attached': $F_{1, 11} = 2.45$, $p > .1$). Importantly, however, we found a significant interaction between stimulus type and attended feature ($F_{1, 11} = 9.48$, $p < .05$), with a larger difference between attended feature (color vs. motion) in the disco condition than the attached condition. This pattern suggests that observers were better able to selectively attend to the task-relevant feature, when the relevant and irrelevant features were attached to (and perceptually attributed to) different surfaces. This result is consistent with the notion of object-based selection; with the disco stimulus, observers could select a task-relevant feature (e.g., color) while ignoring the irrelevant feature (e.g., motion) because color and motion belonged to different objects. On the other hand, with the attached stimulus, discounting the task-irrelevant feature was more difficult; automatic co-selection was increased as the two features were associated with a single object. Importantly, our data suggest that object-based attention, or feature co-selection does not occur simply on the basis of the co-location of features, but is modulated by higher-level cues to surface organization.

However, as seen in [Experiment 1](#), the load manipulation within the color task again failed to modulate MAE strength ($F_{1, 11} = 0.43$, $p > .5$, two-way ANOVA). These data confirm our earlier conclusions, that surplus processing capacity available in the low-load condition was not utilized to process task-irrelevant features, as would be expected by load theory if extended to the feature domain.

It should be noted that there were different local second-order motion signals in the two stimulus conditions. In the 'disco' (non-attached) condition, the isoluminant boundaries separating the color patches of the background were static. In the 'attached' condition, this local conflict between first and second-order motion cues was not present; the color boundaries moved with the disks. If these second-order cues to zero motion had an effect on the measured MAE, it would be to reduce it in the 'disco' condition. This is clearly opposite to the results obtained here. Furthermore, the key result of [Experiment 2](#) is *interaction* between task and condition (disco vs. attached), rather than the difference in absolute MAE magnitudes between the two conditions. We found a larger difference between the high-load motion and high-load color condition with disco stimuli than with attached stimuli. This interaction would be unaffected by any effects of second-order motion components, which were consistent within each condition.

Experiment 3

Our first two experiments suggest that perceptual load for one feature (color) does not affect the level of processing of another, irrelevant feature (motion), when the two features are co-localized. In other words, perceptual load theory does not appear to extend from the spatial to the feature domain. In our final experiment we ask whether our load manipulation within a color-based task can affect motion processing when the two features are spatially separated.

In previous studies, perceptual load was manipulated using word tasks (Rees et al., 1997) and motion adaptation was assessed by MAE duration rather than the nulling task used here. In our final experiment, therefore, we determined whether our color load manipulation can effectively modulate MAEs (measured via nulling) induced at locations separated from the attended color region, in line with previous studies (Chaudhuri, 1990; Rees et al., 1997; Rezec et al., 2004).

Isoluminant colored dots moving in random directions were presented around fixation, and expanding (or contracting) gray dots were presented in the periphery (see [Figure 3a](#)). Participants performed either the low- or high-load color task with respect to the central chromatic dots, while we measured motion adaptation to the peripheral stimulus. If the load manipulation is effective, peripheral MAEs should be larger in the low-load than in the high-load task.

During the adaptation phase, observers performed the low-load color task, the high-load color task or no task (participants passively viewed the adaptation stimulus).

Six observers, including three authors (EWG, ST and WJA) took part in the experiment. All participants except one of the naïve observers had also participated in [Experiment 1](#). Twelve staircases (3 tasks \times 2 motion directions \times 2 staircase directions; 16 trials each) were completed in random order across 6 blocks. All other details of the experiment were identical to [Experiment 1](#).

Methods

The adaptation stimuli consisted of 180 central dots and 300 peripheral dots ([Figure 3a](#)). The central dots (iso-luminant red and green or blue and yellow) were presented within a 1.5 deg radius. These central dots moved in random directions and thus did not contribute to the peripheral MAE (cf., ‘phantom’ MAE, Snowden & Milne, 1997). The peripheral dots were presented within an annulus-shaped aperture with inner and outer radii of 2.5 deg and 4.5 deg, respectively. All peripheral dots were gray and moved according to a coherent expanding or contracting pattern at a constant speed of 1.3 deg/sec. The color and configuration of the test stimulus matched the peripheral part of the adaptation stimulus.

Results and discussion

Task performance

As expected, task accuracy (proportion correct) was significantly higher in the low-load than the high-load color task (0.99 and 0.67, respectively; Wilcoxon signed ranks test, $Z = 2.2$, $p < .05$).

MAE

As seen in [Figure 3b](#), our central load manipulation clearly affected the peripheral MAE ($F_{2, 5} = 7.07$, $p < .05$). The MAE was weaker in the high-load color condition task than the other conditions ($p < .05$ with Tukey’s HSD test). There was no difference in MAE strength between the low-load color task condition and the no task condition.

Thus, in agreement with previous studies (Chaudhuri, 1990; Rees et al., 1997; Rezec et al., 2004), increasing load in our central task decreased peripheral motion processing. MAE strength did not differ between the low-load and no-task conditions; processing of peripheral motion was suppressed in the high-load condition. These results are consistent with the general account of load modulation; only under low-load conditions will the observer’s surplus attention/processing capacity ‘spill over’ from the central attended area to the task-irrelevant peripheral stimuli. Based on these data we conclude that our load manipulation was strong enough to be effective. It seems therefore, that in [Experiments 1](#) and [2](#), attention was selectively directed to either color or motion, but that surplus capacity did not spread to the task-irrelevant feature under low-load conditions. In other words, attentional

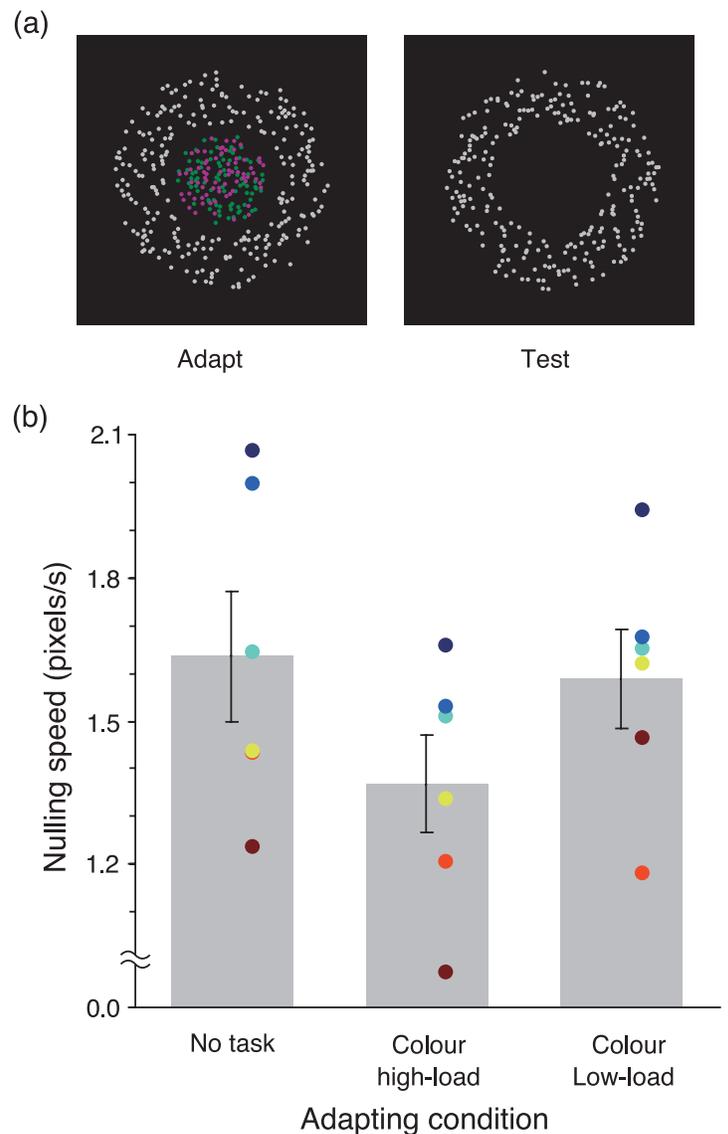


Figure 3. Stimuli and results for [Experiment 3](#). (a) Example stimuli. (b) The resultant MAEs averaged over 6 observers (gray columns) and for individual observers (colored dots).

spread across visual space is dictated by task demands, but attentional spread across visual features is independent of task load.

General discussion

We have shown that, when two features are co-localized, the level of perceptual load applied to one feature (color) does not affect the degree of processing of the other feature (motion) ([Experiment 1](#)). This is true even when the two features belong to perceptually distinct objects ([Experiment 2](#)). Perceptual load modulated MAEs

only when observers directed their attention to the central task-relevant information and motion processing was measured peripherally (Experiment 3). These findings suggest that the effects of perceptual load are mediated by spatial selection, but not by feature-based selection.

In contrast, we found a clear effect of feature selection even when color and motion occupied the same spatial location (Experiments 1 and 2); MAEs were larger when observers attended to motion than when they attended to color. It seems that particular task-relevant features can be attentionally selected at the expense of irrelevant, colocalized features. This effect of feature selection in the absence of load effects on MAEs suggest that the exclusion of task-irrelevant information via feature-based selection does not depend on the level of perceptual load. Task-irrelevant features are suppressed even in situations of low perceptual load.

A number of studies have demonstrated that directing attention to one stimulus feature results in the automatic co-selection of all other features belonging to that object (Blaser et al., 2000, 2005; Melcher et al., 2005; O’Craven et al., 1999; Rodriguez et al., 2002; Sohn et al., 2004). However, our results suggest that attention does not spread equally or completely across all features of an object. In contrast to our demonstration of partial co-selection, Arman, Ciaramitaro, and Boynton (2006, see Experiment 2) reported similar MAEs regardless of whether observers attended to the speed or luminance of an adaptation stimulus (translating random dots), implying that the indirectly co-selected features were facilitated as strongly as the directly attended feature. We speculate that the conflict between their study and our own might be due to the particular features used. It is well established that there are separate pathways for motion and color processing (Livingstone & Hubel, 1984; Maunsell & Newsome, 1987; Zeki, 1978). The magnocellular pathway is considered to be sensitive to luminance contrast and motion, while the parvocellular pathway is considered to be sensitive to color but motion blind. In our study observers attended to isoluminant color while in the Arman et al. study observers attended to luminance changes. It is therefore plausible that our tasks tapped more separable feature-based pathways.

Other studies have also suggested that the visual system can selectively attend to a single feature while suppressing other irrelevant features (Fanini, Nobre, & Chelazzi, 2006; Nobre, Rao, & Chelazzi, 2006; Wegener, Ehn, Aurich, Galashan, & Kreiter, 2008). However, these studies do not directly address the effect of feature-based attention on perception; they measured attentional modulation via a cueing paradigm. For example, in Wegener et al. (2008), observers were cued to the location and feature (color or speed) of an upcoming stimulus change. They found shorter reaction times when the changed feature was correctly cued. However, with such a paradigm, in which the attended visual feature was yoked to a specific task, it is highly likely that cueing changed the response set for the task rather than the processing of the attended feature

per se. In other words, these studies might demonstrate the effect of feature-based cues on the task-specific response set, rather than addressing attentional effect on visual processing. In contrast, we have directly addressed the attentional co-selection of features by consistently measuring the effects of attention on motion adaptation across all test trials. By making a generic task for our observers, independent of the visual features that they were asked to attend, any task-set attentional modulation was eliminated in our study.

Our results suggest that object- and feature-based selection are not mutually exclusive, but both play a role in our observed effects. Experiment 1 demonstrates a role for feature-based attention with larger MAEs resulting from motion tasks than color tasks. However, Experiment 2 showed effects of both object and feature-based attention. When motion and color were attributed to perceptually distinct surfaces (‘disco’ condition), observers were better able to selectively attend to one feature at the expense of another. In other words object-based attention was reduced. Our data provide some support for object-based attentional selection; i.e., attention spreads across an object at which spatio-temporally associated features are bound together (Duncan, 1984; Egly et al., 1994; O’Craven et al., 1999). However, in contrast to previous suggestions (e.g., Arman et al., 2006) the larger MAE in our motion tasks also suggests that any such mandatory co-selection of features is not complete. Moreover, the balance between object- and feature-based attention is not determined by simple co-localization of features but is modulated by higher-order cues to surface organization and feature binding.

Acknowledgments

This research was supported by the Engineering and Physical Sciences Research Council (EP-D039916-1) to WJA and the Wellcome Trust (grant WT080568MA) to NL.

Commercial relationships: none.

Corresponding author: Shuichiro Taya.

Email: s.taya@surrey.ac.uk.

Address: Department of Psychology, University of Surrey, Guildford GU2 7XH, UK.

References

- Alais, D., & Blake, R. (1999). Neural strength of visual attention gauged by motion adaptation. *Nature Neuroscience*, 2, 1015–1018. [PubMed]
- Anstis, S., & Cavanagh, P. (1983). A minimum motion technique for judging equiluminance. In J. D. Mollon & L. T. Sharpe (Eds.), *Colour vision, physiology and*

- psychophysics* (pp. 155–166). London: Academic Press.
- Arman, A. C., Ciaramitaro, V. M., & Boynton, G. M., (2006). Effects of feature-based attention on the motion aftereffect at remote locations. *Vision Research*, *46*, 2968–2976. [[PubMed](#)] [[Article](#)]
- Blaser, E., Papathomas, T., & Vidnyánszky, Z. (2005). Binding of motion and colour is early and automatic. *European Journal of Neuroscience*, *21*, 2040–2044. [[PubMed](#)]
- Blaser, E., Pylyshyn, Z. W., & Holcombe, A. O. (2000). Tracking an object through feature space. *Nature*, *408*, 196–199. [[PubMed](#)]
- Blaser, E., & Shepard, T. (2009). Maximal motion aftereffects in spite of diverted awareness. *Vision Research*, *49*, 1174–1181. [[PubMed](#)] [[Article](#)]
- Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision*, *10*, 433–436. [[PubMed](#)]
- Chaudhuri, A. (1990). Modulation of the motion aftereffect by selective attention. *Nature*, *344*, 60–62. [[PubMed](#)]
- Chen, Z. (2003). Attentional focus, processing load, and Stroop interference. *Perception & Psychophysics*, *65*, 888–900. [[PubMed](#)] [[Article](#)]
- Duncan, J. (1984). Selective attention and the organization of visual information. *Journal of Experimental Psychology: General*, *113*, 501–517. [[PubMed](#)]
- Egley, R., Driver, J., & Rafal, R. D. (1994). Shifting visual attention between objects and locations: Evidence from normal and parietal lesion subjects. *Journal of Experimental Psychology: General*, *123*, 161–177. [[PubMed](#)]
- Fanini, A., Nobre, A. C., & Chelazzi, L. (2006). Selecting and ignoring the component features of a visual object: A negative priming paradigm. *Visual Cognition*, *14*, 584–618. [[Article](#)]
- Handy, T. C., & Mangun, G. R. (2000). Attention and spatial selection: Electrophysiological evidence for modulation by perceptual load. *Perception & Psychophysics*, *62*, 175–186. [[PubMed](#)]
- Kahneman, D., & Treisman, A. (1984). Changing views of attention and automaticity. In R. Parasuraman & R. Davies (Eds.), *Varieties of attention* (pp. 29–61). New York: Academic Press.
- Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. *Journal of Experimental Psychology: Human Perception and Performance*, *21*, 451–468. [[PubMed](#)]
- Lavie, N. (2005). Distracted and confused?: Selective attention under load. *Trends in Cognitive Science*, *9*, 75–82. [[PubMed](#)] [[Article](#)]
- Lavie, N., & Cox, S. (1997). On the efficiency of attentional selection: Efficient visual search results in inefficient rejection of distraction. *Psychological Science*, *8*, 395–398.
- Lavie, N., & Fox, E. (2000). The role of perceptual load in negative priming. *Journal of Experimental Psychology: Human Perception and Performance*, *26*, 1038–1052. [[PubMed](#)]
- Lavie, N., Ro, T., & Russell, C. (2003). The role of perceptual load in processing distractor faces. *Psychological Science*, *14*, 510–515. [[PubMed](#)]
- Lavie, N., & Tsal, Y. (1994). Perceptual load as a major determinant of the locus of selection in visual attention. *Perception & Psychophysics*, *56*, 183–197. [[PubMed](#)]
- Liu, T., Larsson, J., & Carrasco, M. (2007). Feature-based attention modulates orientation-selective responses in human visual cortex. *Neuron*, *55*, 313–323. [[PubMed](#)]
- Liu, T., Stevens, S. T., & Carrasco, M. (2007). Comparing the time course and efficacy of spatial and feature-based attention. *Vision Research*, *47*, 108–113. [[PubMed](#)] [[Article](#)]
- Livingstone, M. S., & Hubel, D. H. (1984). Anatomy of physiology of a color system in the primate visual cortex. *Journal of Neuroscience*, *4*, 309–356. [[PubMed](#)]
- Macdonald, J. S., & Lavie, N. (2008). Load induced blindness. *Journal of Experimental Psychology: Human Perception and Performance*, *34*, 1078–1091. [[PubMed](#)] [[Article](#)]
- Maunsell, J. H., & Newsome, W. T. (1987). Visual processing in monkey extrastriate cortex. *Annual Review of Neuroscience*, *10*, 363–401. [[PubMed](#)]
- Maunsell, J. H., & Treue, S. (2006). Feature-based attention in visual cortex. *Trends in Neurosciences*, *29*, 317–322. [[PubMed](#)] [[Article](#)]
- Melcher, D., Papathomas, T. V., & Vidnyánsky, Z. (2005). Implicit attentional selection of bound visual features. *Neuron*, *46*, 723–729. [[PubMed](#)]
- Nobre, A. C., Rao, A., & Chelazzi, L. (2006). Selective attention to specific features within objects: Behavioral and electrophysiological evidence. *Journal of Cognitive Neuroscience*, *18*, 539–561. [[PubMed](#)]
- O’Craven, K. M., Downing, P. E., & Kanwisher, N. (1999). fMRI evidence for objects as the units of attentional selection. *Nature*, *401*, 584–587. [[PubMed](#)]
- Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision*, *10*, 437–442. [[PubMed](#)]
- Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology*, *32*, 3–25. [[PubMed](#)]

- Rees, G., Frith, C. D., & Lavie, N. (1997). Modulating irrelevant motion perception by varying attentional load in an unrelated task. *Science*, *278*, 1616–1619. [[PubMed](#)]
- Rezec, A., Krekelberg, B., & Dobkins, K. R. (2004). Attention enhances adaptability: Evidence from motion adaptation experiments. *Vision Research*, *44*, 3035–3044. [[PubMed](#)] [[Article](#)]
- Rodríguez, V., Valdés-Sosa, M., & Freiwald, W. (2002). Dividing attention between form and motion during transparent surface perception. *Brain Research: Cognitive Brain Research*, *13*, 187–193. [[PubMed](#)] [[Article](#)]
- Sàenz, M., Buracas, G. T., & Boynton, G. M. (2002). Global effects of feature-based attention in human visual cortex. *Nature Neuroscience*, *5*, 631–632. [[PubMed](#)]
- Sàenz, M., Buracas, G. T., & Boynton, G. M. (2003). Global feature-based attention for motion and color. *Vision Research*, *43*, 629–637. [[PubMed](#)] [[Article](#)]
- Serences, J. T., & Boynton, G. M. (2007). Feature-based attentional modulations in the absence of direct visual stimulation. *Neuron*, *55*, 301–312. [[PubMed](#)]
- Snowden, R. J., & Milne, A. B. (1997). Phantom motion after effects—Evidence of detectors for the analysis of optic flow. *Current Biology*, *7*, 717–722. [[PubMed](#)]
- Sohn, W., Chong, S. C., Pappathomas, T. V., & Vidnyánszky, Z. (2005). Cross-feature spread of global attentional modulation in human area MT+. *Neuroreport*, *16*, 1389–1393. [[PubMed](#)]
- Sohn, W., Pappathomas, T. V., Blaser, E., & Vidnyánszky, Z. (2004). Object-based cross-feature attentional modulation from color to motion. *Vision Research*, *44*, 1437–1443. [[PubMed](#)] [[Article](#)]
- Treue, S., & Martínez-Trujillo, J. C. (1999). Feature-based attention influences motion processing gain in macaque visual cortex. *Nature*, *399*, 575–579. [[PubMed](#)]
- Tsal, Y., & Lavie, N. (1988). Attending to color and shape: The special role of location in selective visual processing. *Perception & Psychophysics*, *44*, 15–21. [[PubMed](#)]
- Tsal, Y., & Lavie, N. (1993). Location dominance in attending to color and shape. *Journal of Experimental Psychology: Human Perception and Performance*, *19*, 131–139. [[PubMed](#)]
- Watson, A. B., & Pelli, D. G. (1983). QUEST: A Bayesian adaptive psychometric method. *Perception & Psychophysics*, *33*, 113–120. [[PubMed](#)]
- Wegener, D., Ehn, F., Aurich, M. K., Galashan, F. O., & Kreiter, A. K. (2008). Feature-based attention and the suppression of non-relevant object features. *Vision Research*, *48*, 2696–2707. [[PubMed](#)] [[Article](#)]
- Yantis, S., Schwarzbach, J., Serences, J. T., Carlson, R. L., Steinmetz, M. A., Pekar, J. J., et al. (2002). Transient neural activity in human parietal cortex during spatial attention shifts. *Nature Neuroscience*, *5*, 995–1002. [[PubMed](#)]
- Zeki, S. M. (1978). Functional specialisation in the visual cortex of the rhesus monkey. *Nature*, *274*, 423–428. [[PubMed](#)]